Geothermal Report

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INTRODUCTION

Geothermal, in literal terms, means earth heat. This heat is thought to be derived from the slow decay of radioactive elements and from frictional forces, both occuring in the earth's plastic mantle. In the continental plates the base of the hardened crust of the earth, called the moho, ranges from 25 to 50 kilometers below the surface of the earth at temperatures ranging from 200°C to 1,000°C.[1] With our present technology drilling depths of 7.5 kilometers have been achieved and may someday reach two or three times that depth. However, the depths from which we may economically extract the earth's heat seems unlikely to exceed ten kilometers.[2]

The average amount of heat which flows to the surface of the earth is 1.5×10^{-6} calories/cm.^{2}/sec.[3] This amount of heat would obviously have to be concentrated considerably to be considered as an energy source. There are, however, areas in which molten rock is, or has been, much closer to the surface. It is in the areas in which natural heat is concentrated close to the surface that economic exploitation may be possible. In this context, geothermal heat is similar to minerals or petroleum in that it becomes economically exploitable when found in sufficient concentrations.

GEOTHERMAL SYSTEMS

Different geothermal areas vary according to geological and hydrological characteristics present at each site. The type of system present determines the type of extraction and production techniques, and to a lesser degree the type of exploration methods which are used in the development of the field.

The system variation is based largely upon the method in which heat energy is transfered at exploitable depths.

A. Dry Rock Systems

Conduction is the dominant means of heat transfer through solids and therefore the earth's crust. In a largely dry rock conduction system, temperature generally increases continously with depth to the interface of the Moho. Differences in heat flowing through dry rock in various areas of the world arise as a function of the depth of the heat source, the thermal conductivity of the crustal rock, and the thermal gradient. At present there are no dry hot rock systems being exploited, although the technology is currently being developed, as will be discussed later.

B. Fluid Systems

Convection is the other primary heat transfer mode present in the earth's crust. This occurs when fluids are heated and rise as a result of thermal expansion and lower specific gravity. Cooling fluids or cooler ground waters replenish the cycle of circulation which is driven by heat furnished at the base of the system. In a convection system the temperatures tend to be greater in the upper portions than in the lower parts due to the nature of the system. There are two basic types of water convection systems which differ according to the physical state of the water.

1. Hot Water Systems

Hot water systems are characterized by water in the liquid state, although it may be at pressures greater than hydrostatic. In a major convection system water serves as the medium by which heat is transfered as it moves from a relatively deep geothermal heat source to the surface or near surface.

Cool ground waters seep into the perimeters of the geothermal system due to their higher density in relation to warmer heated water. The pressure exerted by cooler waters on less dense heated waters may result in artesian hot springs. If the aquifer, a porous water carrying layer of rock, which lies on top of the heat source is covered by an impermible caprock, the water may be at temperatures which exceed boiling at atmospheric pressure. This liquid water, under high pressure, may partially flash to steam once the pressure is released either by drilling or by natural faulting in the caprock layer. Due the fact that all of the water does not flash to steam, and thus droplets are carried up with the steam, this is often called a "wet steam" system.

2. Vapor Dominated Systems

A few percent of the worlds geothermal resources are to be found in the form of vapor dominated systems. At present the only large known systems of this type are found at the Gysers field in California and the Lardello field in Italy. Since they produce superheated steam with no associated liquid, they are often called "dry steam" systems. This steam is generally thought to originate from boiling water in a deep geothermal resevoir with a high temperature heat source and a low water recharge rate. The water resevoir has overlying rock which is highly porous and permible and allows the steam to exist as the continuous pressure controlling phase with pressures below hydrostatic. As the steam rises in the geothermal system it losses its heat to surrounding rock and eventually condenses near the surface in most vapor systems.

This condensed liquid, if not lost to the surface, drains downward on the perimeter of the system to deeper water saturated rock on the perimeters of the heat source and serves as a recharge source for the system.

GEOEXPLORATION

A. Introduction

Geophysical exploration for geothermal energy has been largely adapted from standard geophysical practices, although alterations and various inovations have been found necessary to provide for the uniqueness of geothermal resources. Preliminary exploration selection is based upon a number of previously known geologic factors. The presence of gysers, fumaroles, mud volcanoes, or thermal springs are obvious indicators of geothermal activity. Areas with volcanism of late Tertiary or Quaternary age may also indicate possible near surface heat sources, especially if caldera, cones, or volcanic vents are present. Information available from other activities such as deep minning, well drilling for petroleum, etc., may also provide information pretaining to the possible pressence of geothermal anomalies.

B. Chemical Prospecting

Warm or hot springs, gysers, etc., are very good indicators of geothermal activity and offer a variety of geophysical information when analyzed chemically. Waters, upon entering a geothermal area in a relatively cool state, change in their ability to dissolve minerals, and alter constituents already present, due to the heat or enthalpy added by the system.

The SiO_2 content of geothermal waters is commonly a very good indicator of the temperature of rocks at depth due to a generally consistant relationship between heat source temperature and concentration.[4]

The Na/K ratio in hot spring waters can be a good geothermometer when there is adequate information of competing influences such as other chemicals which may precipitate these ions.

Geothermal fluids are also known to exhibit "oxygen-isotope shift", where the D/H (duterium/hydrogen) and O^{16}/O^{18} ratios are indicative of low lying geothermal heat. Such a shift occurs when geothermal waters seek an isotopic equilibrium with their host rocks. Due to the fact there are large reservoirs of exchangeable oxygen in silicate and carbonate minerals and a reletively small reservoir of exchangeable hydrogen, oxygen ratios shift in heated water and hydrogen ratios don't. Thus, geothermal fluids may be identified and quantified in terms of temperature of the heat source while normal ground waters display no shift.[5]

Once chemistry surveys of geothermal waters have been made, favorable results may indicate further geophysical exploration.

C. Infared Radiation Methods

Another preliminary type of geothermal exploration involves the use of the fact that geothermal areas commonly produce infared heat in amounts greater than background. Such surveys employ the use of infared scanning in the intermediate bands (3-5, 8-14 microns) usually mounted on airborne equipment. Infared exploration of geothermal areas is somewhat limited in its ability to detect small variations of geotermal heat flow. This is due to interference from background noise of solar origin.

Although some interference may be eliminated by predawn survelance, it generally requires a geothermal heat flow of approximately two orders of magnitude greater than background to detect a geothermal anomaly. Infared techniques may be a useful tool in the preliminary exploration of remote areas. However, based on the experience of investigators, infared methods are of limited value in comparison to other geophysical techniques in acessable areas.[6]

D. Earth Resistivity Methods

The earth resistivity method appears to be the most popular and useful technique for geothermal exploration. Resistivity may be used to map the depth, thickness, and extent of the geothermal anomaly. The resistivity of the earth is largely dependent upon the porosity, temperature, and salinity of inerstitial water, all of which tend to lower resistance to electrical current and increase conductivity.

The major drawbacks of this method result from factors which may lower earth resistance and are not related to geothermal activity. These factors may include cold saline waters, and near surface occurance of salt deposits. Because of high conductivity, near surface salts often prohibit investigation at depth.

A typical resistivity investigation is made with four electrodes equally spaced. A D. C. current flows between the two outer electrodes, and the potential drop is measured across the two inner electrodes.[7]

Electrode spacing is determined by resistivity depth sounding during which electrodes may be placed as much as two kilometers apart. Electrode spacings determined to be most characteristic of low resistivities associated with geothermal activity are used with ensueing multiple resistivity transverses. In general, the greater the electrode spacing the greater the depth of penetration, although potenetals of up to 2000 volts may be necessary for maximum depth data. Resistivity transverses are conducted across the entire anomaly, from high resistivity background areas on the perimeter of the anomaly, across the low resistivity area on back into the high resistivity background area. By conducting a series of these transverses on different axes, the low resistivity anomaly may be delineated. However, the selection of method, and interpretation of resistivity data is very difficult and results depent to a large degree upon the experience and skill of the investigator. Topographical features may also interfere with accurate results so this method is best used on flat land. Rough terain is also a restriction in the use of this method due to very long cables to connect the electrodes, and rather heavy generation equipment needed for high depth penetration.

Two methods which depend upon earth resistivity may also have value. Telluric earth currents, which are natural earth surface currents thought to be induced by ionospheric currents, flow over the earth in a sheet-like manner. These currents penetrate to sufficient depths to allow electromagnetic soundings of the earths crust. In magnetic-telluric surveys the varations of the horizontal magnetic field and the varations of the telluric potential across the anomaly are recorded and integrated.[8] Low resistivity may indicate a geothermal anomaly in a manner much the same as does an electrode resistivity survey.

The other resistivity method, radio interferometry, takes advantage of the skin effects of the earth which restrict the penetration of radio wave length energy to great depth. However, in areas of low resistivity, deep penetration is possible. By transmitting radio waves on the surface and recording interference patterns caused by interface reflection as a function of time and distance, low resistance areas can be defined and lower rock structures determined.

The latter two resistivity methods, although not as widely used as the electrode method, do have the advantage of not requiring large amounts of cable. In the case of telluric methods, which do not require a transmitter or generator, application in remote areas is most practical.

E. Seismic Methods

Seismic exploration is based upon the measurement of the velocity of elastic waves through subsurface rock. This measured velocity is proportional to several constants and parameters defined by the characteristics of the rock through which these waves are traveling. In discussing seismic methods two broad catagories, active and passive seismology, can be defined.

1. Active Seismology

Active seismic methods use explosions as a source of elastic waves. There are two suptypes of this method which are refered to as reflection and refraction. The reflection method records the reflection of generated waves off of rock interfaces, faults, and other planer surfaces. Refraction is recorded at some point distant from the wave propagation where the wave emerges at the surface after having traveled through formations of different types on a certian path.

The information obtained from reflection and refration methods can then be interpreted to indicate structural and lithographic conditions of the geothermal field. Although steam and hot water formations have shown particular charateristics of propogation and attenuation of seismic waves, high noise levels present in geothermal areas have made it very difficult to seperate artificially induced waves from natural ones. Thus, although important geologic data such as fault structure, basement shape and depth, and subsurface geologic structure are obtainable, the cost and lack of specificity are limiting factors.[9] It appears doubtful that active techniques will be used as a general exploration tool, but, they can give detailed and special information in geothermal fields.

2. Passive Techniques

Passive techniques are the other type of seismic method. It makes use of the fact that geothermal anomalies generate a large amount of ground noise as a result of characteristic microearthquakes. These micro-earthquakes are thought to arise from tectonic movement associated with geothermal systems.[10] The recording of microearthquakes with a magnetic tape siesmograph can disclose faults and epicenters.

A refinement of this technique records acoustic patterns at certian frequency ranges at a number of points in the exploration area. Studies indicate that each geothermal system has an individual seismic pattern, and that there is a relationship between a geothermal reservoir at depth, high temperature gradients, and high seismic noise levels. If this is a reliable relationship, passive techniques could be very useful in geothermal exploration due to its speed, mobility, and low cost.[11,12]

F. Temperature Surveys

The principle value of temperature surveys is to determine the size and energy content of known geothermal anomalies. Moving, shallow ground waters can mask large and active geothermal systems. For this and other reasons, temperature surveys are not particularly good general exploration devices.

The two most popular types of temperature surveys involve the use of thermisters or thermocouples placed at depths on the order of one meter or at intermediate depths of up to 300 meters.

In the use of shallow one meter holes, changing weather and diurnal fluctuations in temperature can effect temperature measurments. Differential measurments can be made to minimize these effects. The data for a shallow hole survey is usually plotted as temperature and gradient contours over the anomalous area. Due to interference from shallow waters and ground waters, shallow temperature surveys are best used to locate fault lines, etc along which fluids carrying heat circulate.

Intermediate depth surveys aquire temperatures at two or more depths in each hole. Drill holes are usually spaced in a grid pattern or in a polygon. The former is a more accurate method while the latter is less expensive due to the smaller number of drill holes required. The multi-depth temperatures directly indicate temperature gradients and supply data needed for heat flow calculations. Exploration based on heat flow measurements on the order of one meter may be sufficient to indicate the general location of an anomaly, however, to identify potenetial drilling sites, heat flow measurments are usually made at depth.

The major advantage of heat flow data over temperature gradient is that heat flow is independent of the situation conductivity of the different rock types involved. Thus, in heterogenous zones heat flow data can more accurately help determine the most productive areas.

On the basis of temperature surveys the energy production of a system may be calculated, and in conjunction with other geophysical data, production drill hole sites may be selected.

G. Gravity Surveys

Gravity surveys can be used both to outline major geothermal areas or to identify local anomalies. Local gravity anomalies can be caused by burried volcanics, intrusive rocks, or hydrothermally metamorphosed rock. All of these generally display greater rock densities than common sedimentary rock types and thus express themselves as a positive gravity anomaly. These anomalies can be caused by many other features unrelated to geothermal activity and without other supporting geophysical data, interpretation can lead to inaccurate conclusions.

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CHAPTER I

I. INTRODUCTION

II. GEOTHERMAL SYSTEMS

- III. GEOEXPLORATION

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GEOTHERMAL DRILLING

A. Introduction

- There are two phases of drilling which occur in the development of a geothermal field, test drilling and field development drilling.

Test wells are located on the basis of preliminary geophysical exploration. These wells provide subsurface geologic data, information as to the physical and chemical characteristics of the geothermal fluid or rock, help define local productive zones, and help determine the extent and productiveness of the field.

Production testing is the transitional phase between test drilling and the potential production drilling and development of a geothermal field. When a well reaches a possible productive zone of a hydrothermal system, it is developed and tested over a period of time to determine flow rate, composition of fluids, temperature of fluids, recharge characteristics, and other physical properties of the field. Production testing includes, among other things, well venting which cleans the well and is used to provide much of the above information. Well venting is not used in the development of a dry rock system due to the absence of fluids.

If exploration, test drilling, and production testing provide favorable information, the drilling of a number of additional wells to develop the field would follow.

Both production wells and test wells involve the use of almost identical drilling procedures, although test wells may be somewhat smaller and thus require a smaller drilling rig. Rigs may be truck mounted, or a large mast type, depending on the nature of the site and desired future use of the well.

B. Conventional Drilling Methods

Before drilling begins, the site is prepared as a safety precaution. This is done by drilling holes from 50 to 100 feet from the bore hole. Liquid cement is then pumped into these holes under pressure. When hardened a surface skirt is often poured around the drill hole. This makes the ground around the hole stronger and less permeable, thus restricting hot water or steam which might migrate upwards alongside the drill hole and erupt at the surface.

The drilling procedures presently used in the exploitation of geothermal energy are very similar to gas and oil drilling technology. Drilling mud is often used, as in petroleum drilling, to remove debris from the drill bit and to cool and lubricate subsurface equipment. This "mud", usually a mixture of bentonite, water, and chemicals, is pumped down through the drill pipe and bit and returns outside the drill pipe, carrying rock chips from the bit. When drilling through porous or fissured rock the drilling mud may escape into the ground water instead or returning to the surface. In non-productive zones the loss of mud may be controlled by thickening with sawdust, mica chips, etc. These materials block small cracks in the rock and thus stop or lessen the loss of mud. High pressure air or water has also been used to wash drill chips into fissured zones. In production zones the loss of drill cuttings and/or mud into the surrounding rock formation can cause decreased permiability and result in lowered steam or water production. Mud and drill cuttings may later wash back into the completed productin well causing damage to steam and water seperation equipment, turbines, pipes, and other hardware. The use of drilling mud also requires the use of high pressure pumps to circulate the mud through a cooling tower, and storage space, usually in the form of a pond.

The bore is controlled at all times. Well head equipment consists of a "drilling through" valve which allows the bore to be closed when drilling tools have been withdrawn, double control gates, and a blowout preventer operated by remote controls. If dangerous pressures build up the blowout preventer can be closed instantly, and the control gates later, while the drilling tools are still in the hole. The most important control measure, however, is the weight and cooling effect of the column of mud in the hole. The cooling effect prevents steam from forming in the hole and creating excess pressure, while the weight of the column of mud prevents steam and hot fluids from entering the bottom of the drill hole.

Lengths of pipe or casing are used to line the bore hole. This prevents loss of steam or hot water in non-producing zones, borehole contamination by cooler nonthermal waters, and sloughing in fractured zones. The casing is cemented throughout the length of the bore hole to the surrounding rock. This protects the steel from possible corrosion by thermal water and stops the upward flow of thermal water outside the casing. Water enters the hole through a slotted liner suspended from the lower end of the casing, or the casing itself may be perforated with the use of an in-hole mechanical or jet gun.

C. New Developments In Geothermal Drilling Technology

Although the drilling of geothermal wells is very similar to pertoleum drilling, geothermal fields present some problems not encountered in petroleum fields. The heat and abrasiveness found in geothermal formations are extremely hard on subsurface equipment. This includes drill bits, valves, cements, casing, etc. Much of the conventional equipment will not stand up to the physical characteristics found in geothermal systems.

Although drilling technology and associated costs are very important to the development of geothermal resources, little private research has been done in this area due to the relatively small market for special geothermal tools.[1]

The future economic development of geothermal systems which have characteristics that prohibite the use of present drilling technology due to physical and/or economic limitations is dependent upon the developement of low cost drilling. Presently, the cost of drilling increases very rapidly with depth and utilization of geothermal energy at depths greater than 3 km is not economic.[2] The developement of low cost drilling to depths greater than 3 km would permit much greater utilization of the heat energy stored in the outer 10 km of the earths crust.

Plutonic or hard metamorphic rock also limit the use of present drilling technology due to extreme wear on subsurface equipment. High temperatures associated with geothermal systems are also very hard on drilling tools. As a result, costs may be prohibitive to development in geothermal systems with these geologic charateristics.

The Los Alamos Scientific Laboratory has recently been developing drills which bore through through rock by progressive melting rather than by chipping and abrading, This borer is electrically or atomically heated to melt through rock. As it moves, the molten rock hardens and forms an obsidian like casing which is fused to surrounding rock. There is no debris to remove from the hole and it would not be necessary to install casing as the glass liner serves that purpose. High temperature rock improves the preformance of the drill, unlike conventional equipment preformance which is impeded by high temperatures.

A two inch prototype has been developed which consists of a molybdenum shell, a tungsten tip, and a graphite heating element which uses a 3 kw power source. Melting rates have been slow, 60 feet per day. However, calculations show that larger drills should have much higher melting rates as well as increased energy consumption efficiency.[3]

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CHAPTER I

IV. GEOTHERMAL DRILLING

A. INTRODUCTION

B. CONVENTIONAL DRILLING METHODS

C. NEW DEVELOPMENTS IN GEOTHERMAL DRILLING TECHNOLOGY

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GEOTHERMAL ENERGY CONVERSION AND USE

A. Introduction

Powerplant construction would follow in the development of a geothermal system if results are favorable from the the previous development phases of; exploration, test drilling, production testing, production drilling, and field development.

The type and degree of technology used in the development of any particular geothermal system is determined largely by the type of system present (e.g., vapor-dominated, liquid-dominated, dry hot-rocks , and by the chemical and physical characteristics of the steam, liquid, and rock present in that system. In general, respective increasing technological difficulity is encountered with the development of vapor-dominated systems, liquid-dominated systems, and hot dry-rock systems.

The technology for the development and exploitation of vapor-dominated systems, and super heated liquid-dominated systems with low chemical content is developed to a high degree. However, the technology used in the production of power from low enthalpy hot waters and geothermal waters of high chemical content is in a pre-pilot plant stage of development. The technology for the use of hot dry-rock systems is in the early planning and experimental stage.

Power generation from geothermal energy sources is different from fossil and nuclear electrical generation in several aspects. Geothermal plants require no hotbox, boiler, or furnace. Minning of fuels, processing, and transportation to the plant site is not required However, geothermal steam or water cannot be transported over large distance. As a result, geothermal plants are "mine mouth" plants, with the generation facilities sited at the location of of the geothermal field.

- Geothermal power production also requires a much larger volume of steam than does a fossil or nuclear power plant to produce an equal amount of electricity. This is due to the relatively low temperatures of geothermal steam which results in low conversion efficiency. The maximum thermal efficiency of an ideal heat engine is

$$\text{eff.} = \frac{T_1 - T_2}{T_1},$$

where T_1 is the initial temperature in degrees Kelvin and T_2 is the final temperature.[1] Thus, for geothermal generation, as in the Gysers field in California where $T_1 = 452.6^\circ K$ and $T_2 = 299.8^\circ K$ the resulting maximum theoretical efficiency is 33.9 percent.[2] For a fossil fuel plant, where $T_1 = 811^\circ K$ and $T2 = 311^\circ K$, the maximum theoretical efficiency would be 66.1 percent. At the Gysers, a vapor dominated field, only 14.3 percent of the heat energy delivered to the turbine is converted to electricity. At Wairakei, New Zealand the hot water system produces 24 percent steam and 76 percent hot water by weight. 59 percent of total heat produced is in the steam while 41 percent is in the water. Thus the overall efficiency of electrical production from heat produced at the well head is

$$.59 \cdot 14.3 \approx 8 \text{ percent.}$$ [3]

2. Conventional Use of Energy in Vapor Dominated Systems

At present, "dry steam" geothermal systems are more easily exploited, in both technological and economic, terms than are "hot water" and "dry rock" geothermal systems. This is due to the nature of the steam.

In both Lardello, Italy and Gysers, California, the only two known major dry steam fields, the steam carries minerals, wetness, and noncondensible gasses in amounts small enough to allow direct use in a conventional low pressure turbine-generator with little prior treatment.[4]

The steam gathering system of a "dry" steam geothermal field is designed to deliver steam to the generation facility free of moisture and particulate matter, with a minimum practicable loss of energy. Near each wellhead there is a device to seperate particulate matter from the steam. At the Gysers, centrifugal type seporators are used which remove particles down to 10 microns and are 99 percent efficient.[5] After particulate removal at the wellhead, the steam is transported to the power generation station via insulated, steel pipes usually located above the ground surface. To provide for thermal expansion of steam lines, vertical or horizontal expansion loops are spaced at regular intervals along the steam line.

It is not practicable to transport steam over distances greater than one mile.[6] Thus, steam transportation limitations define the maximum area from which steam may be delivered to power generation facilities in any geothermal field using "dry" or flashed steam to generate electricity. Limitations in steam supply to a particular site in a geothermal field has resulted in geothermal power plants of relatively small size, not exceeding 110 megawatts at any site.

At the Gysers there are 10 generation units located in pairs at 5 generation stations. Each station draws steam from an area defined by steam line limitations and field production characteristics. Thus, although each station is relatively small, a geothermal field may produce large amounts of power depending on the size of the field and the number of stations installed.

At the Gysers and at lardello, Italy, conventional, low pressure turbine generators are used to generate electricity. Condensing steam turbines which exhaust below atmospheric pressure are used to utilize the energy of the steam over a larger temperature range, thus increasing efficiency.

This is done by placeing a condenser at the exhaust end of the turbine. The condenser creates a vacuum which allows the steam to expand over a larger temperature range than would otherwise occur.

In the process of condensing the steam, a great amount of heat is released. This heat must be transfered to the atmosphere or some cooling medium. There are three basic types of cooling methods involved. The first is the dry cooling which is similar to an automobile radiator. No water is evaporated into the air and the preformance of the cooling tower is a function of the ambient dry-bulb temperature.

It is also possible to inject the waste heat into the atmosphere via the use of a wet cooling tower in which liquid is cooled by direct contact with the air and by evaporation. Wet towers consume very large amounts of water due to evaporation, however, they are more efficient and less expensive than dry cooling towers.

The third type of cooling method is to use an outside source of water such as a lake or stream, and pass that water through the condenser and discharge the heated water back into the body from which it came. This is generally the least expensive and most efficient method where sufficient amounts of water are available.

Condensed geothermal steam may contain boron, amonia, or other chemicals which render it unsuitable for disposal into surface waters. Such is the case at the Gysers, where wet cooling tower blowdown is delivered back to the steam producer who disposes of it by reinjection into the geothermal system through a nonproducing well.

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C. Conventional Use of Energy from Liquid-Dominated Systems

The technology involved in the exploitation of superheated geothermal waters is very similar, although more complex, to the type of system used in the exploitation "dry" steam systems. There are a number of hot-water geothermal systems presently being exploited for electrical power production throughout the world.[1]

The thermal fluid of a liquid-dominated geothermal system must have certian physical and chemical characteristics to allow exploitation with conventional steam turbine-generator equipment. The fluid must be superheated to a temperature which allows an economic portion of the fluid to be flashed to steam under pressure. Geothermal fluid must not have concentrations of disolved solids, such as SiO_2 or $CaCO_3$, which are excessivly high. If dissolved solids are in high concentration, the steam flashing process will deposit scale on subsurface and surface equipment to such a degree that mainteance and redrilling costs make exploitation uneconomic.

To utilize superheated geothermal waters, the fluid is flashed to steam at a pressure which is determined to give the highest turbine efficiency and the greatest steam volume production. The flashing process occurs in the borehole and in the liquid-vapor separator. At Wairakei, New Zealand hot water makes up about 76 percent (by weight) of the wellhead production after flashing.[2] Cyclone separators are used at each wellhead to finish the flashing process and to seperate the steam from the water. "Dry" steam is collected at the top of the separator and directed into a steam line which is connected to a conventional steam turbine-generator powerhouse.

Water separated from the steam may be disposed of by a number of methods. It can be reinjected into the geothermal formation to help recharge the fluids of the system and slow subsistance. It may al be flashed to steam at atmospheric pressure with the use of expansion towers and mufflers. This process produces large amounts of steam and is the most noticible feature at many geothermal power plants of this type. The remaining fluid which does not flash to steam may be reinjected or cooled and discharged into surface waters.

C. New Developments in the Use of Geothermal Steam and Hot Water

1. Introduction

There are many known geothermal systems which are currently non-exploitable due to their chemical or physical characteristics. "Wet" steam can destroy a conventional turbine in minutes through the corrosive effects of high speed particles hitting turbine blades. Non-condenseable gasses reduce turbine efficiency and create many problems for engineers. Excess scaling in subsurface and surface equipment can cause damage and result in high maintenance costs. If steam flashing causes scaling in the borehole, restricted steam production may necessitate redrilling the hole.

2. Heat Exchangers

Since most of the worlds hydrothermal systems are of the "hot" water type with low temperatures and/or high mineral content, and cannot be used with conventional steam turbine-generator equipment, inovations have been necessary for their exploitation. The use of a heat exchanger to put the energy of the thermal water into another heated substance (e.g., isobutane) is an inovation in which the secondary substance or absorbant is used to power a turbine.

Presently, the U.S.S.R. is operating a 680 kw freon-base generation plant which utilizes water at 81°C.[3] In the U.S. the Magma Power Corporation has developed the Magmamax Power Process.[4]

In this process the entire flow of the geothermal wells is directed into heat exchangers at pressures that do not permit the fluid to flash to steam. The inlet temperature of the fluid can be from 135 – 204°C. The water gives up its heat in the heat exchanger to another fluid (e.g. iso-butane) which is heated, boiled, and superheated. The cooled water is reinjected back into the reservoir from which it came. This maintains underground pressures, prevents subsistance, and recharges the geothermal system.

Iso-butane, in addition to other power fluids such as freons, has the characteristic of having a low boiling point with compariatively high pressure at low temperatures. The superheated iso-butane is expanded through a turbine which then drives a generator. The exhaust gas is condensed in a water-cooled condenser to liquid iso-butane and is then fed back into the heat exchangers, and the cycle is repeated.

The bifluid cycle described has many advantages over the conventional steam turbine-generator system;

1. Geothermal waters are not allowed to flash to steam at any point in the process. This prevents scaling on water conduction equipment and allows the use of geothermal waters with high mineral content for power production.

2. Since water is kept at full pressure its gasses remain in solution and are returned to the reservoir along with dissolved solids without surface water or atmospheric pollution.

3. Utilization of geothermal waters of low enthalpy is possible due to the nature of the secondary fluid used.

3. Helical Screw Expander

A new system for the use of superheated geothermal steam has been developed by Roger S. Sprankle of Hydrothermal Power Company.[5] In this machine, hot water and/or steam is expanded directly in a screw expander. A screw expander bridges the gap between centrifugal type aerodynamic machines (e.g., turbines) and positive displacement machines (e.g., steam-piston engines). It runs at slower speeds than do turbines and, as a result, doesn't have the balance problems which turbines exhibit. The inventor claims that mineral deposition increases efficiency by lapping in rotor-to-rotor, and rotor-to-housing gaps. Excess deposit is continually scraped away and experience indicates that large scars left by solid particles on moving interfaces are filled in with mineral deposits. Although corrosion and erosion are problems, they are less severe than in turbines due to the bulk nature of the expander.

The helical screw expander can use "wet" geothermal steam or superheated water. Other advantages are seen in its high efficiency of 70 percent and its ability to run over a wide range of power loads at a constant speed.[6]

The latter characteristic allows the system to be applied to a large range of geothermal fluid inlet conditions found in various geothermal fields. The wide range of power loads would also permit the power producer to vary generation according to energy demand.

4. Bladeless Turbines

U.S. Fedral Engineering and Manufacturing Inc., of San Diego, California has designed a bladeless turbine which uses "boundry layer drag" to rotate the turbine shaft.[7] "Boundry layer drag" is an unwanted effect in aeronautic design. However, the bladeless turbine uses it as a source of rotational torque without impingement of particles or liquids upon the flat discs which produce the effect.

The bladeless turbine has the advantage being able to utilize "wet" geothermal steam without damage from particulate or liquid. And, due to its simplicity in design and manufacture, it would have a cost appreciably less than that of conventional turbine equipment.

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F. The Utilization of Hot, Dry Rock

1. Introduction

The utilization technology for dry rock geothermal systems is not presently developed on a production or pilot plant basis. If methods can be developed to recover the heat energy of hot, dry rocks, the energy recoverable from this source is estimated to be 100 to 1000 times that available from potential hydrothermal systems.[1] Assuming hot, dry rock systems are technically exploitable, geothermal energy could become a major source of electrical energy for much of the U.S. Estimates of U.S. geothermal resources have been placed as high as 12×10^6 megawatt-centuries with the utilization of hot, dry rock and recent volcanic systems.[2]

To utilize the heat energy of a hot, dry rock system efficiently, it is necessary to create a large heat exchange surface area in a geologic structure, because of the low thermal conductivity of rock. Therefore, all proposed technologies to utilize hot, dry rock systems involve fracturing the hot rock, passing a heat absorbant fluid through the fracture zone, and using the heated fluid to drive an energy conversion device. The two major systems proposed to exploit hot, dry rock geothermal systems differ in the way in which the hot rock is fractured.

2. Hydraulic Fracturing

Hydraulic fracturing is begun by drilling a bore hole well into the hot rock structure. Water is then pumped into the bore hole at high pressure. When sufficient pressure is reached, a tensile fracture will form and increase in size as pumping is continued. The usual result of hydraulic fracturing is a radiating disc-shaped fracture, which may be up to several kilometers long but only a few centimeters wide. The plane of the disc usually has a vertical orientation due to the geometry of stress conditions found in the pressurized hole.

After the crack has formed, a second hole would be drilled to intercept the upper portion of the disc-shaped fracture. Water would then be pumped down the first hole and circulated through the fracture to absorb heat. The hot water would then be retrieved through the second hole and circulated through energy conversion equipment. After the heat energy has been extracted at the ground surface, the cooled water can then be reinjected into the "down" hole.

Water in the liquid phase would be used to bring the heat energy to the surface. As much as 10 times more thermal energy may be transmitted up a pipe if the working fluid is water rather than steam.[3] Because the water can be carried up the hole at full temperature without flashing to stream, the wells are less likely to plug from dissolved salts.

It may not be necessary to pump the cool water into the "down" hole. The cool water would be considerably more dense than the rising hot water. The differential weight between the two columns of water would generate an automatic pumping pressure of several hundred pounds per square inch.

A bifluid system of energy extraction at the surface appears to be the most practical at this time. Thermal energy would be transferred in a heat exchange to another fluid such as isobutane which would drive a turbine. (See Ch. I, Part D2)

There has been no field experience in hydraulic fracturing of geothermal resources. In a dry rock geothermal system the results may be different than described above for two basic reasons. One of these arises from the fact that most dry rock geothermal systems are thought to be composed of inhomogeneous granitic material. Thus, fractures may not develop in a symetrical fashion. The second is a consequence of thermal stress induced by utilizing cold water to hydraulically fracture hot rocks. The differential shrinkage of hot rock as it is cooled by inflowing water is expected to induce additional cracks which may propagate themselves. For these reasons, the fracture pattern is expected to be more complex than it is in nonthermal rock. Thermal stress cracking may cause propagation of the system over time, and thus the fracture system may be self-sustaining for energy utilization purposes.

3. Nuclear Stimulation of Hot Rock

Dry, hot rock may be utilized by creating a highly fractured zone with nuclear explosives. This is done by drilling one or more bore holes into a dry geothermal formation. A nuclear device is fired in each drill hole to create a fully contained "chimney" of fractured rock. Another bore hole is drilled to intersect the top of the "chimney." Water is then pumped into the "chimney" through fillpipes, heated, and returned to the surface for utilization in power generation equipment. The primary cycle is closed due to the presence of radioactive elements in the heated waters. After energy extraction, the radioactive water would be reinjected to the fracture zone.

Battelle Northwest, the Atomic Energy Commission, American Oil Shale Company, and Westinghouse have conducted a study of the feasibility of Plowshare geothermal power.[4] The study concluded that Plowshare geothermal power was technically feasible, and that under certain conditions electricity could be produced for from 5 to 7 mills/kwhr. To exploit one cubic mile of rock at 350°C cooled to 100°C, which would produce 3700 MW for 30 years, on the order of 40 to 60 nuclear devices would be required to fracture the rock.[5] To be economic today the 350°C rock would have to be within 10,000 feet of the surface and devices with sizes of greater than 200 KT would be required.

The economics of this system are quite sensitive to the costs of drilling and blasting. Large nuclear devices (on the order of 1000 KT) require less drilling and blasting than does the use of several smaller devices. However, the shock associated with the use of large devices is substantial. To avoid this effect the detonation of several smaller devices has been proposed.

In areas where topography allows, the construction of the power generation facility on a barge in a canal system has been proposed.[6] This would allow the plant to be withdrawn from the generation site during further development of the fracture system. Field development may proceed over a period of many years if this system were used. If topography is not suitable for a mobile generation facility, the plant could be built to withstand the ground shock or all of the devices required to supply the lifetime energy needs of the plant could be fired prior to plant construction.

4. The Marysville Project

In 1969 Dr. David Blackwell of SMU discovered an area of abnormally high heat flow near Marysville, Montana. Heat flow in this area has been measured as high as 19.5 ucal/cm^2sec as compared with an average heat flow of 1.9 ucal/cm^2sec for western Montana.[7] Dr. Blackwell estimates the volume of the heat flow source to be over 64km^3, less than 5km. in depth with temperatures of 700°C at 2.5 km depth.

If Dr. Blackwell's estimates are accurate, the energy between 700°C and 200°C is sufficient to support 41,000 megawatts for 30 years.[8] The hot rock would have a full value of 25 billion dollars.

Battelle Northwest has been given a $2,588,935 grant by the National Science Foundation.[9] The funding will support phase I of a proposed two phase project to develop the resource at Marysville. Battelle, working with Southern Methodist University and Rogers Engineering, will investigate the nature of the anomaly and determine how it might be developed as an energy resource.

Under Phase I of the project, the research team will explore, drill, and model the anomalous area. This involves three major developmental steps which include: (1) A geophysical resource survey consisting of heat flow and resistivity measurements, gravity and infrared surveys, and microseismic analysis. Geophysical data is to be compiled and analyzed to select a deep well drilling site. (2) Drilling, coring, and logging a well which is planned to reach either a depth of 6000 feet or temperatures of 700 to 900°F. (3) The potential of the resource will be evaluated for further exploitation. This will include physical and chamical analysis of the cores, analysis of the logging data, geophysical modeling of the system, and well tests for heat removed. This data is to be compiled to plan and prepare for phase II - resource development. Phase I of the project should be completed by October of 1975.

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E. On Site Use of Geothermal Energy

1. Introduction

Geothermal energy derives its major economic importance from the fact that it can be converted to electricity, which can then be transported to areas of energy use. However, in the conversion of geothermal energy to electricity, power transmission, and reconversion of electricity to work, there are substantial losses of energy. Electric generation and transmission systems require high capital investment costs. If energy costs rise sufficiently in the future, agriculture, industry, and communities may develop around geothermal energy sources in order to make more efficient and economic use of the resource.

Multipurpose use of geothermal energy may make geothermal exploitation more economic and efficient. A multipurpose system integrating power generation, water desalination, and mineral recovery from geothermal brines has been proposed for the Imperial Valley area of California.[1] The huge amounts of heat rejected by geothermal power generation plants could be put to local agricultural, domestic, or industrial use.

2. Space heating

Geothermal waters are used for space heating throughout the world in a variety of situations. Thermal waters which are presently uneconomic to exploit for electrical production are most often used for space heating purposes, although most hydrothermal systems can be used for this purpose.

Heating with geothermal waters can result in substantial savings in fuel costs. Geothermal waters are being used to heat homes in Iceland, New Zealand, Hungary, U.S.S.R., the United States, and in other countries.

In Iceland, the city of Reykjavik furnishes geothermal heat for 90 percent of the buildings with a consumer savings of 40 percent over the cost of oil.[2] This use of geothermal energy represents 220,000 tons of oil per year and greatly reduces air pollution sources resulting from combustion. In the U.S. thermal waters heat homes in Klamath Falls, Oregon; Boise, Idaho, and various other locations in the western states.

In the U.S.S.R. low enthalpy thermal waters supply enough energy to heat 2×10^7 M^2 of greenhouses. Iceland, Japan, and Italy also use large amounts of agricultural heating supplied by geothermal energy. Geothermal greenhouse projects, small in comparison to foreign developments, have been constructed in Lakeview, Oregon; Wendal, California; and Brady Hot Springs, California.[3,4]

3. Air Conditioning

In Rotorua, New Zealand a hotel uses geothermal energy to drive a LiBr heat pump which serves as an air conditioner for the hotel.[5] Construction costs were competitive with conventional air conditioning systems and operating costs are 5 percent of conventional system costs.

4. Industrial Use

The direct use of geothermal energy in industrial processes has been somewhat limited due to the "mine-mouth" status of direct geothermal use. However, rising energy costs may make low cost geothermal evergy more lucrative to exploitation by industry in the future. Any industrial process which requires direct use of heat or steam could conceivably use geothermal energy in its plant operations.

The Tasman Pulp and Paper Company in Kawerau, New Zealand uses geothermal steam for timber drying, log handling equipment, and for generation of 10,000 KW of electricity.[6]

In Japan, geothermal energy is used to produce salt from sea-water by evaporation.[7] A plant in Namafiall, Iceland uses geothermal steam to dry deposits of diatomite.[8]

Due to the ability of hot water to dissolve and carry minerals, geothermal water can produce chemicals or minerals which are in sufficient concentration to extract economically. In the past, dry ice, boron, and various salts have been extracted from thermal waters commercially. Future geothermal development may be aided by the extraction of valuable by-products such as potassium, lithium, calcium, and other metals.[9]

5. Recreational Use

The utilization of geothermal springs for health purposes, bathing, and recreation dates to ancient civilizations and constitutes a considerable revenue source in some areas of the world. In Montana, there are fifteen commercial establishments which advertise geothermal pools, mud baths, and steam rooms to attract local and tourist trade.[10]

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[1]Dragone, G., and Rumi, O., 1970, Pilot greenhouse for the utilization of low-temperature waters: Geothermics, Spec. Issue 2, v. 2, pt. 2.

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Chapter II

ENVIRONMENTAL IMPACT

E. Power Production from Hot, Dry Rock Geothermal Systems

1. General

2. Stimulation and Production of Power from Hot, Dry Rock using Hydrofracture

3. Stimulation and Production of Power from Hot, Dry Rock using Nuclear Devices

   a. General

   b. Nuclear Detonation Effects and Hazards

   c. Radiation Hazards

   d. Power Production and Plant Operations

Chapter II - ENVIRONMENTAL IMPACT

INTRODUCTION

The environmental impact associated with the development of a particular geothermal system will be largely dependent upon a number of conditions found at the site and upon the type and degree of technology used to develop that site. Because geothermal fluids cannot be transported efficiently over distances greater than one mile, geothermal energy conversion and/or direct use must occur at the resource local. Thus, geothermal energy use is, by necessity, a "mine mouth" situation where energy use or conversion must take place at the resource site. As a result, the major portion of environmental impact due to geothermal development will take place at or near the location of the geothermal resource.

The type of geothermal system present, (e.g. vapor-dominated, liquid-dominated, or hot, dry rock) will determine, to a large extent, the type of exploitation technology used. Thus, the environmental impact of development will be largely dependent upon the physical nature and chemical characteristics of the system. Other physical factors which influence the impact of development would include the biological characteristics of the area, hydrologic factors, geographic location, demographic considerations, meteorological conditions, and other geologic characteristics. The aesthetic, recreational, historical, industrial, mineral resource and other potential land uses must also be taken into consideration prior to the development of any geothermal resource.

The three basic types of geothermal systems produce different environmental considerations. Vapor-dominated systems produce steam which is relatively free of elements and other gases, while liquid-dominated systems often produce highly mineralized waters. The exploitation of liquid-dominated systems may produce subsidence effects not encountered in the development of vapor-dominated systems. Exploitation of hot, dry rock may produce a number of very different environmental effects related to the technology of ground preparation (e.g. nuclear stimulation). Geothermal development of an area will generally follow a sequence of exploration, test drilling, production testing, field development and plant construction, energy production, and post plant operations, each with its own type and intensity of environmental impact.

PRELIMINARY EXPLORATION

The environmental impact associated with the preliminary exploration for, and geophysical analysis of, a geothermal system is dependent upon the locality of exploration and methods of exploration used. The exploration of potential or known geothermal resources is designed to locate and define economically exploitable geothermal reservoirs. Exploration activities may include geophysical operations (See Chapter I), drilling shallow temperature gradient wells, construction of access roads, air borne exploration, and cross-country transit by foot, vehicle, or animal.

Whenever there is increased activity of humans and machinery in an area, there is corresponding danger from accidental forest fire or brush fire. In Montana, the development of any geothermal field is expected to be most rapid during the warm summer months when the fire hazard is highest. Sparks from equipment, burning of waste, and carelessness may result in accidental fire. It is assumed that the fire hazard would remain the same throughout all phases of development of a geothermal site.

During the exploration phase, shallow geothermal gradient holes will be drilled. Gradient holes should be capped when not in use to prevent small animals from falling into them and to prevent injury to larger animals.

The activity of low flying helicopters and aircraft, used for thermal and magnetic surveys, and for the collection of geologic structural information would have a temporary effect upon larger animals in the area and would be disturbing to human inhabitants.

The impact of geoexploration would be dependent to a large degree upon the present land use of the area in question. Most surface exploration requires a physical presence upon the land. Roadless or wild areas would be subject to irreversible environmental impact if it were necessary to build access roads for gradient drilling and other geophysical instrument vehicles. Increased use of preexisting roads would increase local dust, noise, traffic, etc. for the duration of exploration activities. Other exploration activities would include the intensive use of trails, removal of vegetation for an explorative site, and the movement of heavy vehicles and equipment cross country. These activities would result in increased runoff, erosion, stream sedimentation, loss of habitat, and wildlife. The result of explorative activity could be visually observable for a number of years, depending on the site.

Exploration upon lands in the control of either the U.S. Forest Service or the Bureau of Land Management would be subject to the rules and regulations of the agency trusted with the administration of that land. Wilderness areas are an exception to this rule. The Wilderness Act of 1964 allows the area land management to exclude motorized vehicles from wilderness areas to maintain the character of the area. Thus, many modes of explorative practices are excluded from use in wilderness areas. Further, all mineral rights in wilderness areas must be established by 1983 on the basis of explorative data. As a result there would be no explorative work done in designated wilderness areas past 1983. Exploration upon private lands is, of course, in the control of the land owner. Administration of state lands will be discussed in Chapter III.

TEST DRILLING PHASE

A. General

After a lease or other exploitation rights have been obtained, test drilling will be conducted in the geothermal area which has promise. Locations for the drilling of test wells will be chosen on the basis of explorative geologic and geophysical data. The location of test wells and access roads therefore may be in conflict with other surface use. Conflicts of interest may be acute where the ownership of the surface and ownership of the geothermal "extraction rights" are not held by the same entity.

Test drilling equipment usually consists of a truck mounted rig and portable air compressor or water pump, depending on whether drilling is done with air or water. The drill site is cleared of vegetation and is graded to a flat surface. "Mud" pumps, "mud" tanks, generators, drill pipes, racks, tool house, and other equipment are usually located on the drill site. Storage tanks for fuel and water may not be on the drill pad, however they would be located in the vicinity.

Test drill pads require a level area of at least one half to one acre to facilitate equipment use. In rough terrain, access roads and pad preparation may require blasting and considerable grading. Resulting impact upon the surface of the area may be substantial.

Geothermal anomalies are commonly located in areas of high aesthetic value. This is primarily the result of a correlation of areas of recent volcanism and tectonic movement with geothermal systems. The aesthetic value of an area would be degraded with the advent of drilling due to road building, site preparation, and the location of machinery and men in the area.

Test drilling would alter the recreational value of the area. The use of drill rigs, air compressors, pumps, earth moving equipment, and other machinery would require increased noise levels which would result in a direct adverse effect upon the users of the area. Big game and other animals would leave the area as a result of noise and other activity. Further, wildlife mating and migration may be disrupted in some areas. At Gysers, noise from the drilling operation was measured at 126 db(A) at 25 feet and 55 db(A) at 1,500 feet.[1*] It would be necessary to control the hours of drilling operations near populated areas.

Geothermal drilling and other associated activity may increase the recreational use of an area. Construction of roads into an area previously non-accessable to vehicles could increase recreational use. The novelty of geothermal resources may also add attraction to an area for recreational purposes. The presence of drilling activity, venting steam, large steam plumes, and associated noise has created a substantial tourist attraction at many presently developed geothermal sites.

As a result of physical land modification, surface waters may become degraded as a result of clearing, earth moving, and drilling operations. These impacts would be temporary in nature but could result in localized damage to fish and wildlife.

Blowouts of uncontrolled thermal waters or steam would create

*db(A) decible value measured using an A weighting network of a standardizing sound meter. This system is used in the enforcement of the Occupational Health and Safety Act of 1970.

an environmental hazard in the development of a geothermal area. When a blowout occurs, it is difficult to handle due to the temperature of the thermal fluid. However, unlike petroleum drilling, there is no danger of fire. The possibility of mishaps during the test drilling phase is greater than in following phases due to the unfamiliarity with subsurface geologic and physical conditions. However, blowouts could occur during all ensuing phases of geothermal development and after abandonment of operations.

In addition to blowouts at or near the drill hole, thermal fluids may erupt some distance from the borehole as a result of drilling.

The possible effects of blowouts and other mishaps include pollution of air with gaseous and particulate matter, pollution of surface waters, pollution of ground waters, noise pollution, waste of the resource, and safety hazards to the work crew during the blowout and during control procedures. The principal effects of the chemicals and gases contained in geothermal fluids will be discussed later in this paper.

All of the major hydrothermal systems which have been developed for power production have experienced blowout difficulty. At Larderello, Italy blowouts occur regularly during drilling. Because of the cavernous geologic structure, drill crews often experience loss of circulating fluids or "mud". This causes the hydrostatic head of circulating fluids to fall below that of the steam. When this happens the steam comes up the pipe resulting in a blowout. Equipment and techniques have been developed at Larderello to bring the well under control.[2,3]

Three blowouts have been reported at the Gysers, California in 1957, 1970, and 1973. There have been approximately 100 wells drilled at the gysers from 1957 to 1973. The 1957 blowout was attributed to inadequate casing and landsliding. As of February 1973, the blowout had not been controlled. During the 15-year period it is estimated that this blowout has emitted 9 million tons of steam, 4,000 tons of hydrogen sulfide, 5,000 tons of amonia, and 6,000 tons of methane. The energy resource loss is approximately $125,000 per year.[4]

In 1970 another well blew out through a fissure 65 feet from the well head. Cement was injected into the well casing over a period of ten days to control the blowout. The well was sealed and abandoned.

In 1973 a landslide apparently ruptured the casing of a producing well. A steam explosion occured which resulted in the formation of a crater fifty feet across.

In the development of the Wairakai field in New Zealand approximately 100 wells were drilled during the first years of development. Of these, two wells were abandoned due to blowouts during drilling and another was abandoned as a result of a blowout after a few years of steam production.

During the drilling of Bore 26 at Wairakai a break in the casing occured at 600 feet due to subsurface fault slippage.[5] Within a few days steam discharging from the area increased substantially. A second slip occured and was followed by an explosion and flow of hot mud. There was no loss of life, however, there were injuries. After drilling equipment had been removed from the drill site, another explosion occured, covering the drill site with 6 feet of rock and mud. The blowout was eventually controlled by drilling a deviated hole to intersect Bore 26 below the casing rupture. Cement and gravel were pumped into the second hole to seal and control the blowout.

Other geothermal blowouts have occured in North America. These areas include Cerro Prieto, Mexico; Klamath Falls, Oregon; and a few sites in California. Also, three capped wells in Beowawe, Nevada have been dynamited by unknown persons. The Nevada wells remained uncontrolled for a number of months, however, emittant water was of sufficient quality for surface irrigation.

Well blowouts present a danger to people in the area, as well as degrading the quality of air, surface water, and ground water resources. The severity of the environmental impact of a blowout would be dependent upon the physical nature of the blowout, the chemical properties of the steam and/or water, and the type and degree of technology and caution used to prevent and control the mishap.

B. Hot, Dry Rock Systems

The test drilling phase of the development of a hot, dry rock geothermal system would entail much of the surface environmental impact encountered in the development of a hydrothermal system. Test drilling for hot, dry rock would, in general, require substantially fewer holes to determine the power production capabilities of the system. Also, due to the expense of drilling in rock of plutonic origin, the number of holes per project may be fewer. Thus, the test drilling phase of hot, dry rock systems would generally have a smaller overall surface impact.

The possibility of a blowout during this phase of development of a hot, dry rock system would be remote. However, if a hydrothermal system not indicated by preliminary exploration were encountered, a blowout could result. Other overlying pressurized fluids or gases such as petröleum or natural gas could also result in a blowout.

PRODUCTION TESTING

A. Hydrothermal Systems

Production testing is the transitional phase occuring between test drilling and the potential economic development of a geothermal resource. A test well which has penetrated a potentially productive zone is tested over a period of time to determine its flow rate and to clear it of debris. Other parameters tested include: the chemical composition of fluids and associated gases, pressure of the well, recharge rate, compressibility, and other physical data concerning the geologic structure and its contained fluids.

The testing of a hydrothermal system requires the venting of wells to the atmosphere for periods as long as several weeks or months. This is done until the well flow stabilizes at a uniform level. During this period noise would reach its maximum level. Air quality problem associated with particulate, chemicals, and noncondensible gases would also reach its maximum on a per well basis during the production testing stage of development. Condensed steam and/or hot water entering surface waters or high quality ground waters could also result in substantial environmental impact.

1. Air Quality

Geothermal fluids will vary greatly in content of chemicals and noncondensible gases, depending upon the type of system present, the geologic makeup of the area, the origin of the water, the temperature of the system, and other in site factors.

a. Gases

Noncondensible gases are often carried by geothermal fluids. These gases include hydrogen sulfide, carbon dioxide, methane, hydrogen, argon, nitrogen, amonia, and radon. Vapors of boric acid and mercury may also be present. Although the combined total of these gases is usually less than three percent of the steam fraction, they can result in substantial air quality degradation when released to the atmosphere in sufficient amounts.

At the Gysers, California a vapor dominated geothermal field, the noncondensible gases constitute from .2% to 1.8% of the steam flow.[6] Of this 82.5% is CO_2, 6.6% is CH_4, 1.4% H_2, 1.2% inert, 4.5% H_2S, and 3.8% NH_4. Although gases are present in small concentrations, some may present a hazard to human health. The bleeding and venting of noncondensible gases to the atmosphere during production testing and ejection of noncondensible gases from condensers during power production could present a health hazard to people on the plant site.

Table II-I indicates the toxic levels of certain gases for comparison to the levels of gases found in the steam at Gysers, California; Larderello, Italy; and Namafjall, Iceland. Hydrogen sulfide is the most dangerous hazard, being present in the steam at concentrations from 7 to 25 the toxic level. Amonia is another possible health hazard, present at from 5 to 6 times the toxic level at the Gysers and Larderello, respectively.

A health hazard could result in a topographic region (e.g. mountain

Table II-I

Gases associated with geothermal fluids at various locations and comparison with toxic levels in percent

	Gysers 1/ California	Larderello 2/ Italy	Namafjall 2/ Iceland	Toxic level
H_2O	98.045	98.08	99.43	-
CO_2	1.242	1.786	0.18	.50
H_2	0.287	0.037	0.19	-
CH_4	0.299	-	0.01	1.00
N_2	0.069	0.0105	0.05	--
H_2S	0.033	0.049	0.14	.002
NH_3	0.025	0.033	-	.005
H_3PO_4	0.0018	0.0075	-	-

1/ White, D. E., (Reference 8)

2/ calculated from: Lindal, B., (Reference 9) valleys) where H_2S could accumulate locally from a geothermal operation. H_2S is detectible by humans at .03 ppm (45 ug/m^3).

Stanford Research Institute used a box model to calculate the possible buildup of hydrogen sulfide and amonia in a hypothetical mountain valley over a period of one day.[7] Emission rates from geothermal site were estimated at 45,000 lb/hr for hydrogen sulfide and 63,000 lb/hr for amonia. The box used was 10 km on a side with a height or mixing depth of 0.3 km. Light winds, moving in one direction through the "box" at 5 km/hr for 14 hrs. a day, simulated moderate stagnation conditions in a mountain valley situation. The low speed winds resulted in a daily total volume of 200 cubic kilometers. One day's output diluted in 200 km^3 resulted in a concentration of 2500 ug/m^3 for H_2S and 3500 ug/m^3 for amonia. Thus, the concentration for H_2S would be 50 times the odor threshold. The odor threshold for amonia is 35,000 ug/m^3. The study indicates amonia accumulation at one tenth this level. At STP, 3,500 ug/m^3 NH_3 is equivalent to 50 ppm NH_3. The toxic level for NH_3 is 10,000 ppm.

Hydrogen sulfide is oxidized to sulfur dioxide in the atmosphere within 2 to 48 hours.[10] SO_2 and its oxidation product (SO_3) are both soluble in water and can be washed out of the air by rain. The formation of acid rain from a large geothermal operation emitting H_2S could help create environmental hazards quite removed from the geothermal site.

Carbon dioxide is present in some geothermal steam at several times its toxic level. Because its density is greater than air it could accumulate in topographic lows. However, when vented to the atmosphere at low velocities component separation does not take place.

Thus, in most situations carbon dioxide should not be a problem. Adequate ventilation in buildings, condensers, etc. would prevent danger from CO_2 buildup.

Methane is present in geothermal fluids in varying amounts. Since it is lighter than air, it would not build up to dangerous levels when vented to the atmosphere. It is a natural product of biologic decay, and is oxidized to water and carbon dioxide in the upper atmosphere.

Radon, a gaseous decay product of uranium, is associated with hot springs and liquid-dominated systems. At present, this source of radiation has not been shown to pose a significant possible increase to our present total radiological burden. However, monitoring at each site should be required to assure public health protection.

Mercury is present in most thermal waters. Because of its ability to vaporize, it could pose an air quality problem in some geothermal developments, although water quality problems are more likely to be encountered as a result of the presence of mercury. During production testing amounts of mercury may become airborne and pose a potential hazard as long as the wells remain vented. Mercury is easily "washed out" of the air by precipitation. As it reaches the surface, it can enter the food chain causing effects documented in many studies.

b. <u>Dissolved solids and other material</u>

During production testing venting wells may inject large amounts of particulate into the atmosphere. Wells may also be vented during later stages of development. This may be done for cleaning purposes or it may occur when the generation facility is "down". Thus, when conventional generation methods are used, the venting of wells may take place throughout the life of the plant.

A study conducted by the University of California was made to determine the elemental composition of particulate in the Gysers area and to determine if the Gysers geothermal plant had an adverse effect upon that composition.[11] No significant differences were found between upwind and down wind sites during sampling on a day with steady 10 knot winds. However, on the second sample date winds were light and significant changes were noted in particulate concentration from upwind sites to downwind sites. Table II-II indicates significant increases in S, Cl, K, Ca, and Fe. None of the Gysers power units were in the production testing phase in May 1972. However, only one of the ten units capable of producing power was on line on May 25. Because nine units were "down", most of the wells in the area were being vented to the atmosphere. Thus, this situation simulates the air quality effects of the production testing phase of a vapor-dominated geothermal field.

Because liquid-dominated steam often carries greater amounts of particulate than does "dry" steam, the adverse effects of the venting of these wells will, in general, be greater than the effects of venting "dry" steam. Due to the great chemical variation found in geothermal waters and steam, the impact of production testing would have to be predicted on the basis of water and steam chemical analysis for each individual site.

c. Meteorological considerations

The production testing phase of the development of a hydrothermal system would inject large amounts of moisture. If this were to occur in mountain valleys or similar restricted air sheds, an increase

Table II-II

AVERAGE OF THREE DOWNWIND SITES, ALL STAGES

May 25, 1972
Gysers, California

9:30-11:30 A.M.

	Upwind (ng/M^3)	Downwind (ng/m^3)	Δ (ng/m^3)	Δ (%)	Significan Increase
Si	770±230	604±181	-166±294	-21±38	
P	411±123	745±224	+335±255	81±62	
S	210±63	507±152	+297±164	141±78	*
Cl	310±93	382±115	+ 72±148	23±48	
K	0±15	80±24	+ 65±28	> 434±189	*
Ca	0±15	176±53	+161±55	> 1073±367	*
Fe	103±31	184±55	+ 81±63	79±61	

11:30-2:00 P.M.

	Upwind (ng/M^3)	Downwind (ng/m^3)	Δ (ng/m^3)	Δ (%)	Significan Increase
Si	750±225	994±298	+245±373	33±50	
P	468±141	503±151	+350±207	7±44	
S	64±19	400±120	+336±122	525±190	*
Cl	0±15	261±78	+246±79	> 1673±530	*
K	18±5	35±11	+ 18±12	102±69	*
Ca	0±15	114±34	+ 99±37	> 657±248	*
Fe	77±22	174±52	+ 97±57	125±73	*

Cahill, T. A.,(reference11)

in humidity and fog could be predicted. If temperatures were below freezing at the time, localized iceing of roads and vegetation could also occur.

2. Water Quality

During the production testing phase of a hydrothermal system, there will be varying amounts of water in a liquid state available to enter surface and/or ground water systems. The amount of liquid water available is largely dependent upon the type of system present, either vapor-dominated or liquid-dominated. The venting of a vapor-dominated system would result in either no condensate or a very small amount. Because vapor-dominated systems carry relatively small amounts of dissolved solids and produce little condensate upon venting, they have a relatively small effect upon water quality during the production testing phase. Liquid-dominated systems produce large amounts of liquids which vary greatly in their chemical makeup and concentration of elements and compounds. In general, the liquids resulting from liquid-dominated systems are much higher in chemical content than is the condensate resulting from a "dry steam" system.

Table II-III indicates the large variation in chemical makeup of geothermal waters. It should be noted that it is not likely that geothermal waters would be found in Montana with dissolved salts concentrations similar to those of Cerro Prieto, Mexico. However, chemical makeup should be expected to vary considerably.

To adequately determine the flow and other characteristics of a "flashed steam" well, the water is usually separated from the steam during production testing. The effect of this water upon the environment will be dependent upon the fashion in which it is treated

Table II-III

COMPOSITION OF GEOTHERMAL FLUIDS

Parts per million by weight

Name	The Geysers (1)	Norris Basin (2)	Well 4 (3)	Cerro Prieto (4)
Location	California	Wyoming	New Zealand	Mexico
System type	Vapor Dom.	Hot Water	Hot Water	Hot Water
Component				
Sodium	.12	439	1,130	5,610
Potassium	.10	74	146	1,040
Calcium	.20	5.8	26	321
Lithium	.002	8.4	12	14
Magnesium	.06	0.2	0.1	negative
Strontium	.10	n.a.	n.a.	28
Barium	n.a.	n.a.	n.a.	57
Silver	n.a.	n.a.	n.a.	trace
Copper	n.a.	n.a.	n.a.	trace
Chlorine	20.00	744	1,930	9,694
Boron	.10	12	26	12
Fluorine	.10	4.9	6.2	trace
Sulfur	7.10 (sulfate)	38 (sulfate)	35 (sulfate)	10
Silicon Dioxide	.50	529	386	n.a.

(1) Koenig, 1970 (Reference 12)
(2) White, 1963 (Reference 13)
(3) Banwell, 1957 (Reference 14)
(4) Rex, 1970 (Reference 15)

and disposed of. To avoid repetition the alternatives for the treatment and disposal of thermal liquids will be discussed in chapter II, under Full Scale Development and Power Production.

3. Noise

One of the major impacts of the production testing phase, is the production of noise. An unmuffled well venting high pressure steam can produce noise measured near the source on the order of 135 dB(A).* The threshold of pain is 120 dB(A), however, there are mufflers available to reduce this problem. Experience at the Gysers has shown that noise can be reduced to 100 dB(A) at 25 feet from the vent.[16] At a distance of 1,500 feet the noise produced from a muffled well was measured at 65 dB(A). For comparison purposes, a jet aircraft produces 125 dB(A) at 200 feet.

Greatly increased noise levels would be disturbing to residents and workers in the area of activity. Measurements of noise levels to determine potential health hazards and lesser, but objectionable noise levels should be conducted.

b. Hot, dry rock

The physical process involved in the production testing of a stimulated hot, dry rock system is not available in the literature. Because there is no water or steam contained in this type of system, there would be little to test for until a fracture system were created and water was introduced to the system. This technology will be discussed in the following section.

*dB(A) decible value measured using an A weighting network of a standardizing sound meter. This system is used in the enforcement of the Occupational Health and Safety Act of 1970.

FULL SCALE DEVELOPMENT AND POWER PRODUCTION

A. General

If production testing and all other previous phases prove successfull, the full development of the geothermal field may follow. This would include drilling enough production wells for generation of power, construction of steam or hot water lines, road construction, transmission line construction, powerhouse construction, and finally, power production. This process involves the long range committment of land and resources and in many instances, involves an irreversible impact upon the environment. The extent of this impact will be dependent upon the total spectrum of problems related to resource production, conversion, and transmission, and upon the care exercised by all persons involved in the development of the system. If proper steps are taken to insure a minimum of impact, in the development of geothermal energy, this source of energy could become an important, relatively nonpolluting source of economically feasible power generation.

B. Construction

The development of a geothermal area requires substantial modification and use of the surface of the land. The large amount of activity involved in the construction of wells, steam lines, power lines, power house, and roads will generate a broad range of effects upon the area involved.

1. Land Use

Perhaps the most important consideration in the development of a geothermal area is the change in land use patterns. Geothermal power production involves considerable earth movement, noise, road construction, visual change, and alteration of air and water quality. Prior to beginning the construction phase, a very extensive amount of environmental planning should be involved to insure a minimal impact upon the land and its uses. Historical, aesthetic, agricultural, recreational, and other uses should be considered in the master plan of the development. Although the impact of development upon these uses would be large, care on the part of both public and private institutions would insure a minimal impact.

In terms of environmental impact it is most useful to view the land area used to produce and carry energy to the powerhouse as replacements for mining, oil drilling, fuel processing, transportation, and other similar facilities associated with the production of energy from fossil or nuclear power plants. When viewed in this manner, the land committment involved in the production of energy from geothermal sources is not as consumptive nor potentially permanent as are its substitutes. A 1000 mw plant may require six to eight square miles of land, providing efficient utilization.[17] Terrain, lease considerations, and other physical factors could require a 1000 mw plant to effectively cover ten to twelve square miles.

In comparison, ten square miles of stripable coal land containing 50,000 tons per acre could supply a 1000 mw fossil plant for approximately 100 years. This does not take into consideration the land requirements for transportation or plant siting. Further, geothermal land use is not exclusive of other land uses as is strip mining, nor does it entail complete removal of the land surface.

Within this area, pads must be prepared for the drilling of production wells. At the Gysers wells are spaced at approximately one per forty acres averaging about 8 MW per well.[18] At Cerro Prieto, Mexico, a "wet" steam system, wells are spaced at about 10 acres per producing well. Roads must be constructed to each drill site for access and maintenance purposes. The construction of drill pads and roads requires the removal of vegetation and, if the area is of uneven topographic character, various amounts of earth movement will be required. Steam or hot water pipes must also be constructed to carry heat from the well over distances of up to one mile to the powerhouse.

The construction of the power house and its accessory facilities requires a level area of considerable size. Geothermal power plants usually have rather low silhouettes. Cooling towers located adjacent to the power house are often much larger than the generation facility and much more noticable due to the large plumes of steam which are created in the cooling process. The construction of power lines would also require vegetation removal for tower construction and the removal of trees located in the path of the right-of-way.

This network of steam pipe, access roads, a multiplicity of steam plumes from a variety of sources, excavations necessitated by drilling operations, power house, and transmission lines are visual byproducts of full scale development. Unfortunately, a geothermal resource must be developed where it is found, if it is to be utilized. For this reason, certain areas of high scenic, recreational and agricultural value may, in the interest of a total quality environment, be exempted from geothermal development by state, county, and federal action.

In areas of development where terrain is rough, land modification becomes most extensive. Extensive land modification is apparent at Wairakei, New Zealand, a liquid-dominated system. The development of the Gysers has also resulted in large amounts of earth movement for roads, drill pads, power house, and steam lines.

One possible way to minimize the impact of drilling and steam pipe upon the surface of the land would be to drill several deviated holes from one drill pad. This would lessen the number of drill sites required as well as reducing the number of pipeline branches.

Although the development of wells and pipeline would result in considerable land alteration and aesthetic degradation, it should be noted that geothermal development and other possible surface uses are not mutually exclusive events. In Larderello, Italy and in the Broadlands, New Zealand, geothermal wells and pipes have been located in agricultural areas with a minimal impact upon agriculture.

An expenditure of effort on the part of developers and administrative agencies to insure that geothermal development harmonize with its surroundings, would help insure a minimal visual impact upon the area. Such planning has not been the case at many geothermal developments throughout the world. The U.S. Department of Interior wrote the following statement concerning the visual impact of the Gysers:

> "The high visibility of the Gysers development in California deomnstrates a degree of visual impact where little special attention has been given to aesthetic placement of buildings and transmission lines and where camouflage techniques have not been used to blend pipelines, transmission lines or buildings to the natural setting."[19]

It has been necessary to construct pipelines above ground to allow for thermal expansion and contraction. At Wairakei, New Zealand the pipe expands 22 feet in the longest steam main.[22] Thermal expansion loops are placed at intervals in the steam line. These expansion loops often have a vertical orientation to allow vehicular traffic to pass underneath the steam line. The visual impact of above ground steam lines and expansion loops could be minimized with environmental planning in the placement of wells and lines. Further lessening of impact would be possible with the use of camouflage techniques to blend power production facilities, pipe lines, and transmission lines with the surroundings.

During construction there will be considerable activity, noise, dust, etc. If the geothermal site is remote, it may be necessary to construct living quarters for construction crews, and later for operation employees. This would cause more intense use of the area and would require further surface use, population impact, sanitary impact, and other accessory developments such as small businesses, recreation facilities, etc.

C. Power Production from Vapor-Dominated Systems

a. Air Quality

It is assumed that future use of vapor-dominated geothermal systems would use conventional steam generation equipment for the production of electricity. Because "dry" steam is relatively free of chemicals and can be fed directly into a steam turbine, the use of the steam in this manner is the least costly means of production per kilowatt.

There are three major air quality problems involved in the production of power from a "dry" steam system. The first involves non-condensable gases which are present in the steam and are injected into the atmosphere during the power cycle. The second is the large amount of moisture which is injected into the atmosphere from cooling towers. The third is the aerosols and particulate which enter the atmosphere as a result of venting wells or steam lines.

Non-condensable gases are drawn from the direct contact condensers which liquify the steam after it has passed through the turbine. These gases are either directly ejected into the atmosphere or are carried to the cooling towers where they can enter the atmosphere. Non-condensable gases may also enter the atmosphere during the production phase from vented wells or steam lines. The possible effects of these gases are discussed in Chapter II under PRODUCTION TESTING.

The most hazardous of the non-condensable gases is hydrogen sulfide. To adequately evaluate the sulfur emissions of this type of geothermal plant, it would be desirable to compare emissions to fossil fuel plants. Because H_2S is oxidized to SO_2 within 2 to 48 hours after entering the atmosphere, a comparison is reasonable. The Gysers steam contains .0225 percent hydrogen sulfide. Of this, 30 percent is returned to the reservoir with the steam condensate.[21] With a 16 percent thermal efficiency, the Gysers plant produces 4 grams of sulfur per kilowatt hour of electricity, while a coal fired plant with a 40 percent thermal efficiency can produce 2.3 grams sulfur per kilowatt hour of electricity produced under EPA standards.[22]

The Gysers power plant is developing a new method to remove H_2S from the gas stream. It uses iron or nickel to catalyze precipitátion of sulfate as sulfur in a scrubber located in the plant's cooling tower.[23] Although this system is still experimental, it has achieved 90 percent removal of H_2S. Thus, catalyzed precipitation of sulfur from a wet gas stream is developed explicitly for geothermal energy. Should it prove successful on a production scale it would reduce sulfur emissions from power house outflow substantially. Because Montana has stringent standards for the ambient concentration of H_2S, there is reason to believe that ambient standards for H_2S may be violated if the steam content of H_2S were on the order of 3 to 5 times higher than the H_2S concentration found at the Gysers. Air stagnation conditions would also compound this problem.

The Montana H_2S Standard reads as follows:

> "0.03 ppm, $\frac{1}{2}$-hour average not to be exceeded more than twice in any 5 consecutive days. 0.05 ppm, $\frac{1}{2}$-hour average not to be exceeded over twice a year."

Heat and moisture from cooling towers of geothermal power plants have a high potential for climatic influence where topographic conditions restrict air shed volume. Because geothermal power plants have low thermal efficiencies, they have correspondingly high rates of rejected heat. Once through cooling causes environmental problems in the body of water used as a heat sink. For this reason, the atmosphere is used to absorb waste heat through the use of the wet cooling tower. Such towers are much less costly than dry cooling towers. Attempts to predict the meteorological effects of these plumes are becoming more important, particularly if power production facilities are placed in mountain valley areas where stagnation conditions can be magnified by wet plumes. Some of the possible effects associated with wet plumes are increased cloud cover, induced rain, and more severe weather.[24] Increases in humidity have been associated with natural-draft towers on the East coast. Increased fog and ice has received the greatest amount of attention in relation to wet cooling towers.[25] An EG&G investigation mapped a geographical distribution of potential adverse effects from cooling towers.[26] The distribution indicates areas of high, moderate, and low possible adverse effects based on fog, low and level inversion, and mixing depth frequency. It shows that the western third of Montana is in an area of high adverse potential. This area corresponds with a large portion of the areas in Montana classified as "Areas Valuable Prospectively" for geothermal resources by the U.S. Geologic Survey.[27]

The final air quality problem associated with a "dry" steam generation facility concerns aerosols released from wells being vented for cleaning purposes , when the plant is "down" or off load, and the venting of steam lines for measurement or other purposes. These practices would be carried out on a sporadic basis over the life of the plant. The preceding section on production testing (Chapter II, Section) describes this process and its effects.

2. Water Quality

The effects of a "dry" steam geothermal development upon water quality are dependent upon the chemicals present in the cooling tower condensate, the size of the operation and the method of disposal of tower condensate and other liquid streams.

In 1960 Pacific Gas and Electric began power production at Gysers Unit I, discharging tower condensate into Big Sulphur Creek.[28] By 1968 two more units were discharging condensate into the creek. The condensate from the two latter units had higher concentrations of amonia salts, boron, and hydrogen sulfide. In 1968 a major fish kill occurred in Big Sulphur Creek resulting in near eradication of steelhead and a severe salmon kill. The North Coast Region Water Quality Control Board determined that the levels of chemicals entering the creek from direct condensate disposal was responsible for the fish kill.

The major alternatives to direct disposal of condensate into surface waters are treatment for removal of certain chemicals from condensate and reinjection of condensate into the ground. Treatment of condensate is costly and of unpredictable reliability due to the lack of technology development. Union Oil, the steam supplier at Gysers, reinjected the condensate at the perimeter of the field. This appears to have no adverse effect and may help to replenish the supply of water to the field and thus prolong its use.

It is apparent that the condensate from the relatively clean "dry" steam field may produce an environmental hazard to surface waters if it is not treated. The elevated temperatures of these waters could also cause thermal pollution if directly injected into surface waters.

Reinjection of condensate appears to be the least costly, most reliable means of condensate disposal. Although it may replenish ground water resources, it can have adverse impacts. If condensate is reinjected into strata bearing high quality waters, the quality of those waters may be permanently degraded. Incidents of seismic activity relating to the injection of fluids in waste disposal systems have occurred at the RockyMountain Arsenal near Denver.[29] If the injection pressure necessary for disposal were greater than hydrostatic, reinjection could lubricate and extend existing fractures causing increased seismic activity.[30] However, if reinjection is at pressures less than hydrostatic, which is the case in many hydrothermal systems, the chances of seismic stimulation are greatly reduced because return of fluids simply maintains pre-existing pressures in the reservoir.

3. Other Effects

The production of power from a "dry" steam geothermal system could have a large variety of additional effects upon the environment.

The use of natural steam for power generation purposes represents the utilization of a resource which is not renewable in a time scale which is comparable to that of the life of the production facility. Withdrawal of steam by power production facilities is, in general, greater than the recharge rate of that system. Measurements at the Gysers show an average exponential decay with a five year half life at one well per five acres.[31] This implies that over a 20 year lifetime a unit with the above well spacing would fall to $1/16^{th}$ of its initial production rate, thus requiring the drilling of 16 times the number of wells needed initially to maintain given production level. Larger spacings of wells, such as 20 or 45 acres per well, will lead to approximately the same amount of generation capacity per square mile because the decrease in number of wells per area is compensated for by increased well lifetime. Thus, intensive use will lead to a high generation capacity with a short life span while wider spacing will result in a correspondingly longer life span with a lower generation capacity. The total power capacity per unit of land is determined by the nature of the steam resource and not by the way it is tapped. However, if a high well density, short life span spacing is used, more wells would be required than if a longer time base for depletion is used. Although a lower generation capacity requires an extended presence upon the land, it does not require the number of drill pads, roads, etc. that are necessitated by drilling a well every few acres. Thus, it would appear that a geothermal system which is planned for a relatively long lifespan would have less impact than an extensive use system due to the smaller amount of pollutants released per unit time, steam pipe, and earth movement required.

D. Power Production from Liquid-Dominated Geothermal Systems

1. General

There are several possible methods of producing electrical power from "hot water" geothermal fields. One method is to flash water to steam and then use the steam to drive conventional low pressure generation equipment. This process is used, among other places, in New Zealand and Mexico.[32,33] Another process uses heat exchanges and a separate working fluid to drive turbine equipment (see chapter I part). At present, a heat exchanger unit is in operation in the U.S.S.R., however, there is little information available pertaining to this plant.[34] Other possible techniques of hot-water power generation include the use of bladeless turbines and mechanical expanders (see Chapter I, part). Processes using mechanical expanders or bladeless turbines have not been developed on a production scale.

The environmental impacts associated with the development of a "hot water" system would be very similar to the impacts associated with "dry" steam systems in terms of land use, construction, fluid lines, power house, earth movement, etc. However, the impacts of the utilization of this type of system upon the air and water quality will vary according to the type and degree of technology used in energy utilization.

The major difference between the impacts of these systems depends upon the physical state of geothermal fluid (liquid or vapor) which is used to produce electrical power. If the geothermal fluid remains as a liquid, the circulation of geothermal fluids would, for most purposes, remain a closed system. As a result, the geothermal fluid would not be in direct contact with the ambient environment. It is expected that this fluid would, after use, be reinjected into the geothermal system for recharge. However, it could be treated and ejected to the surface.

If the production technology uses "flashed steam" or "wet steam" to produce power, the geothermal fluid may come in contact with the ambient environment after use. Further, in the steam-water separation process there are inherent environmental problems. Steam condensate and water which is not flashed to steam could then be returned to the system or ejected at the surface.

Because the geothermal fluid is in its liquid state in a liquid-dominated system, there are adverse effects associated with the use of "hot" water systems not associated with "dry" steam systems. In a "dry" steam system "boil off" from deeper water reservoirs replaces the vapor which is withdrawn for power production. Thus, subsidence is not expected to occur in the development of a "dry" steam system.

This is not the case in the development of liquid-dominated systems. Subsidence can occur whenever support is removed from below the surface. In a liquid-dominated system pressures are greater than hydrostatic. This constitutes an over pressured reservoir where the fluids present are supporting the overlying column of rock. If water is removed from the reservoir and is not returned, subsidence may occur. At Wairakai, New Zealand, where hot water is withdrawn from the system and discharged to the surface, the ground level has subsided as much as 11 feet in some areas.[35]

Hot-water systems would also experience a greater potential for seismic activity due to reinjection than would vapor-dominated systems. Because the steam pressure in a vapor-dominated system is less than hydrostatic, the gravitational pressure of a column of water in the rejection well is enough to force the waste water back into the system. However, because hot water reservoirs are often at pressures above hydrostatic, pumping will be required to force the waste water back into the system. Injection of fluids at pressures above hydrostatic has been associated with incidents of seismic activity at Baldwin Hills Oil Field, California and at the Rocky Mountain Arsenal, Colorado.[36,37] In such instances, pressure could open and lubricate faults and thus increase seismic activity.

The close association of geothermal areas and zones of tectonic activity or zones of crustal spreading and convergence is well documented.[38,39] The role of fluid pressure changes in seismic activity is not well known. Reinjection at pressures above hydrostatic could stimulate earthquakes; however, to date such stimulated seismic activity has not been severe. There is reason to believe that reinjection, lubrication, and stimulation of local fault systems tends to relieve regional stress, thus mitigating the severity of large earthquakes. Further, reinjection of waste would extend reservoir life potential by decreasing net fluid withdrawal.

2. Flashed Steam Use of Liquid-Dominated Systems

The surface effects of using flashed steam in conventional generation equipment will be much the same as the impact of the use of a vapor-dominated system. This is because both systems use the same technology of generation once the steam has been separated from the water. There are, however, significant differences in the impact of "flashed steam" system use versus "dry steam" system use. These differences are related to the nature of the system itself. A "flashed steam" generation plant will produce about 25 percent steam by weight.[40] Thus, there is a large amount of water, heat, and dissolved chemicals which must be dispensed. Because two-thirds of the steam fraction is evaporated in the cooling towers, it follows that a "flashed steam" generating plant would have about 10 times as much heated waste water to be reinjected, or otherwise treated for disposal.

"Hot water" systems often carry much more dissolved solids than do vapor-dominated systems. As a result, the rejected water of this type of generation system may have increased impact upon the environment due to its high volume flow and also because of elevated concentrations of dissolved solids.

In Wairakei, New Zealand, a hot-water flashed-steam plant, the reject water is not treated and is dumped directly into the river. In addition to thermal pollution, this hot water has been found to constitute a significant source of mercury pollution.[41] Inorganic mercury discharge from these sources accumulates in sediments and often microbial methalation is concentrated in the edible tissue of fish. Average concentrations in excess of .5mg Hg/Kg have been found in trout populations in receiving bodies of water discharge. This is the maximum concentration considered acceptable for human consumption.

Alternatives to direct discharge include water treatment and reinjection. Because of the volume of discharge which is produced by this type of generation, treatment is considered to be very expensive and also not reliable. Reinjection has been discussed in the previous section. Unless waste is disposed of by injection to high quality ground waters or significant seismic stimulation is indicated, reinjection appears to be the most practical, reliable method of mitigating the impact of reject water and heat.

3. Continuous Liquid Phase Use of Liquid-Dominated Systems

The use of liquid-dominated systems in a bifluid generation system where the geothermal fluid remains a liquid throughout the process would appear to have the least overall environmental impact of any geothermal power production discussed (see Chapter I, part). The geothermal fluid does not come in contact with the environment throughout the power process and would be reinjected to the system as a liquid. There is no chemical pollution of air and water. Further, there is a remote chance for subsidence because all of the water removed is returned to the periphery of the system by reinjection. Because the fluid remains a liquid, pipes from the well head to the power house would be smaller because of the decreased volume necessary. The major air or water quality impact resultant of this type of system would be thermal pollution. It would be necessary to use a body of water or a closed system of water and dry cooling towers to condense the isobutane or power fluid after it has been used in the turbine to generate electricity. Because of the expense of dry-cooling towers, it is expected that wet cooling towers would be used. In areas where cooling water is not available, some geothermal water may be used consumptively in cooling towers to complete the cooling process. In this situation, geothermal waters would be in contact with the ambient environment and could cause air quality problems similar to those associated with the use of cooling towers in a conventional dry or wet steam power generation facility.

E. Power Production from Hot, Dry Rock Geothermal Systems

1. General

The development of a hot, dry rock geothermal resource exists only on paper at this point in time. As a result, it is difficult to accurately predict the impact of this type of development upon the environment. Up to and through the drilling stage of geothermal development this resource would have largely the same impact upon the environment on a per well basis as does the development of hydrothermal systems. Past this point, these systems vary greatly in the technologies used for development. To extract heat energy from a hot, dry rock system requires the formulation of a fracture system in the rock to provide adequate heat transfer surface for the introduced fluid to absorb enough heat for the production of electricity (see Chapter I, part).

There are two generally accepted methods by which a sufficiently large fracture system can be induced in a hot, dry rock geothermal structure. These methods are hydrofracture and nuclear stimulation.

2. The Stimulation and Production of Power from Hot, Dry Rock using Hydrofracture

After a hole has been drilled to intersect a hot, dry rock structure, the major impact of hydrofracture will concern seismic and water consumption factors.

There is increased potential for seismic activity due to stimulation by hydrofracture. To initiate a tensile fracture in volcanic rock will require a pressure on the order of 7,000 psi above hydrostatic at the depth of the fracture.[42] This is sufficient fluid pressure change to trigger seismic activity. However, minor seismic stimulation could mitigate the shock associated with a larger regional earthquake by relieving local stress in rock structures.

Thermal contraction of heated rock due to heat withdrawal will cause a void space in the fracture system ranging from one-fourth to one-half cubic foot for each million Btu withdrawn from the rock. Thus, a 100 MW plant would require 25,000 gallons of makeup water each day. If there were underground leakage from the reservoir, this number could be increased substantially.

After the fracture system has been formed via hydrofracture, liquid water would be used to transfer heat to the surface.[43] A dry, hot rock system fractured and utilized in this manner would be nearly identical to a liquid-dominated system in its capability for use upon the surface. The environmental impacts possible would be similar to those created by the production of power from a liquid-dominated geothermal system (see Chapter II, part).

3. The Stimulation and Production of Power from Hot, Dry Rock using Nuclear Devices

a. General

There is substantial possible adverse environmental impact associated with the detonation of an underground nuclear device to create the fracture system necessary to utilize hot, dry rock. Although there are no presently existing nuclear-stimulated geothermal sites, there is substantial information available on the impact of underground detonation of nuclear devices. In addition to the 250 underground detonations conducted for military purposes at the A.E.C. Nevada Test Site, there have been three Plowshare projects conducted for peaceful use of nuclear devices outside of the Nevada Test Site. These Plowshare tests include: the "Gnome" detonation near Carlsbad, New Mexico in 1969; the two "Gasbuggy" events near Farmington, New Mexico; and the "Rulison" event near Grand Valley, Colorado. These experimental projects provide foundation information to predict the impact of nuclear stimulated geothermal resources.

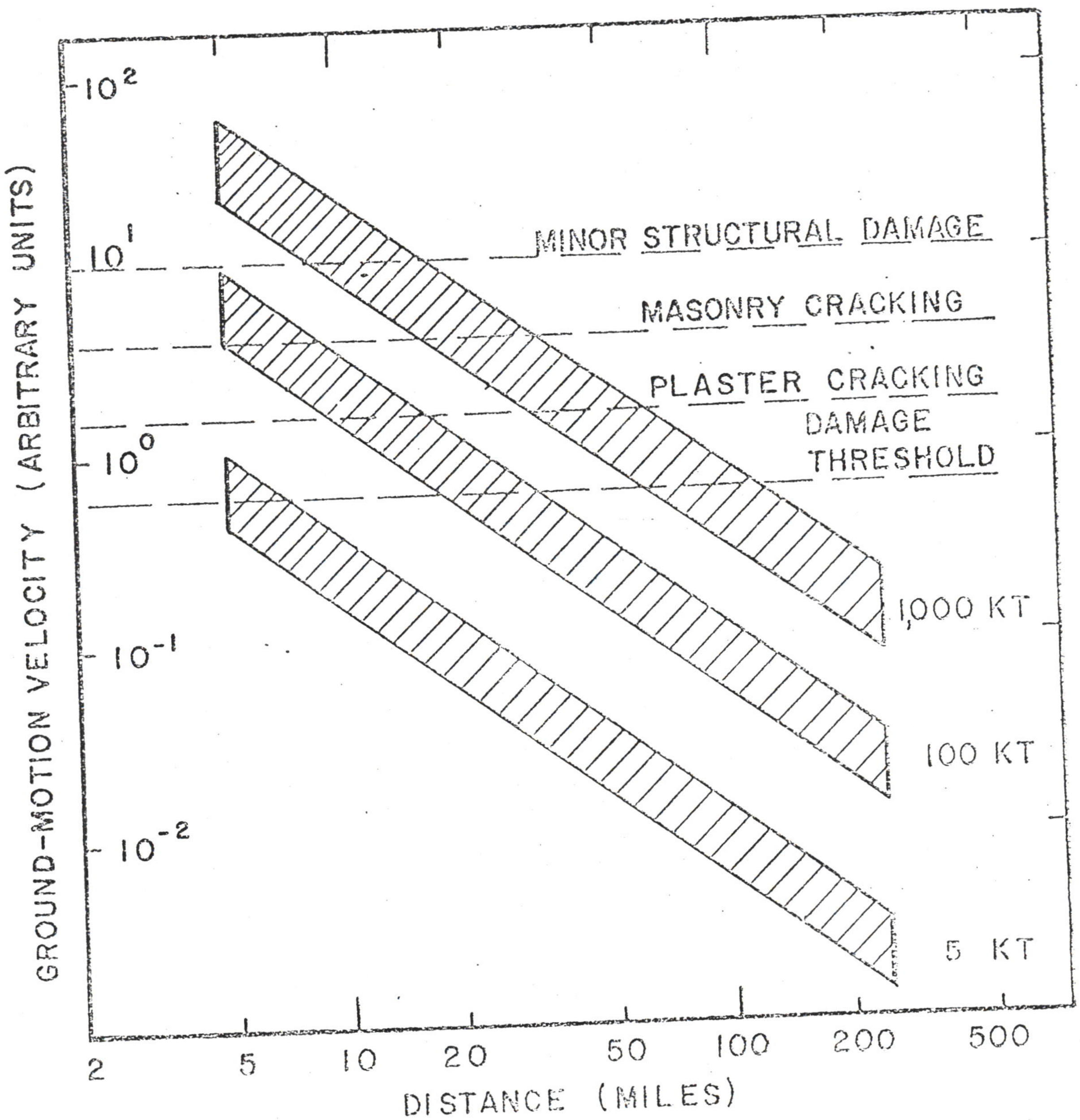
Prior to the detonation of a nuclear device for geothermal stimulation purposes, it is extremely important that adequate information is collected to determine the safety, technical feasibility, economic feasibility, and environmental hazards involved in the use of nuclear devices at any particular site. Because of the nature of radionucleotides in terms of toxicity and persistence, it is necessary to collect extensive impact data sufficient to evaluate the possible hazard involved during detonation, plant operation, and during a post plant period of several hundred years.

b. Nuclear Detonation Effects and Hazards

The nuclear detonation effects associated with stimulation of hot, dry rock are a result of the liberation of energy sufficient to vaporize rock and create a spherical cavity. The pressure of the explosion drives a shock wave outward in all directions. When the wave hits the surface, the ground vibrates in a fashion similar to that of an earthquake. Geologic formations, vegetation, and man-made structures can suffer from this vibrational ground motion. Humans, animals, and vegetation can incure injury or death from falling debris resulting from ground motion. Trees, plants, and ground cover can also be destroyed by breakage, landslides, and root damage. Ground motion could also change patterns of water drainage and may damage local water quality. Building damage at different levels of severity could also occur, depending upon the distance separating the building from ground zero. Table II-IV demonstrates structural damage from various sizes of nuclear devices as a function

Table II-IV

SEISMIC DAMAGE ASSOCIATED WITH
UNDERGROUND NUCLEAR EXPLOSIONS



Sandquist, C.M., and Whan, G.G., (Reference 42) of distance in miles from ground zero. Building damage from a 1000 kT explosion would be large and damage from a 100 kT device could cause serious problems, depending upon the location of the site in relation to populated areas.

In an area of high seismic activity, which is often the condition at a geothermal site, a seismic event might occur sooner than it would naturally as a result of nuclear detonation. However, nuclear detonation could reduce the impact of natural earthquake by relieving stress in fault systems which could otherwise build up stress levels sufficient to cause a major earthquake.

Surface extrusion of molten rock or the triggering of volcanic eruption is a possible result of underground detonation of nuclear devices. The likelihood of these events occurrence is dependent upon the proximity of magma and open fractures to the detonation site.

Thermal water near or overlying the detonation site may exist at temperatures sufficient to flash water to steam. A pressure release induced by nuclear detonation could cause the water to flash to steam and cause a hydrothermal explosion.

c. Radiation Hazards

There is potential for the release of radioactive elements to subterranean waters, the surface and the atmosphere during and after the detonation of an underground nuclear device. The bulk of the energy released by an underground nuclear explosion is a result of fusion which is quite "clean" in terms of radiation production. However, a fusion reaction requires a fission triggering device of 3 kT. Fission is responsible for most radioactive material present after detonation. The fission trigger produces approximately 200 isotopes of 36 elements. Further, induced radioactive materials are produced by neutron capture in the surrounding rock material. Table II-V indicates the radioactivity of nuclides present in significant amounts resulting from detonation of four different nuclear devices which could be used for geothermal stimulation.

The means by which nuclear detonation could contaminate the surrounding environment include: seepage to ground waters, prompt venting to the atmosphere, and delayed venting or seepage to the atmosphere. Of these, prompt venting entails the greatest potential hazard to human health.

The radioactive nuclides most likely to be involved in prompt venting or delayed seepage to the atmosphere are the gaseous elements xenon, argon, krypton, iodine, and tritium. In a prompt venting incident, the initial distribution of radioactive materials would be dependent upon local meteorology and topography. In most cases, the fallout area would be confined to an expanding corridor downwind from the point of venting. On the basis of tests conducted at the Nevada Test Site, it is unlikely that more than 5 percent of the total radioactivity present would escape in the event of a maximum prompt venting accident. Table II-VI indicates estimated infinite-isodose lines for a 2 to 5 percent release of radioactivity resulting from the prompt venting of a 100 kt fission-fusion nuclear device. The table is a representation of exposure under prevailing wind conditions. It is apparent that this type of incident could have a serious impact up to 30 to 60 miles from the geothermal site.

TABLE II-V

Initial Radioactivity from Some Radionuclides of Greatest Environmental Concern, in Kilocuries, for Various Sizes and Types of Detonations: A, Fission-Product Activity; B, Induced Activity in Igneous Rock

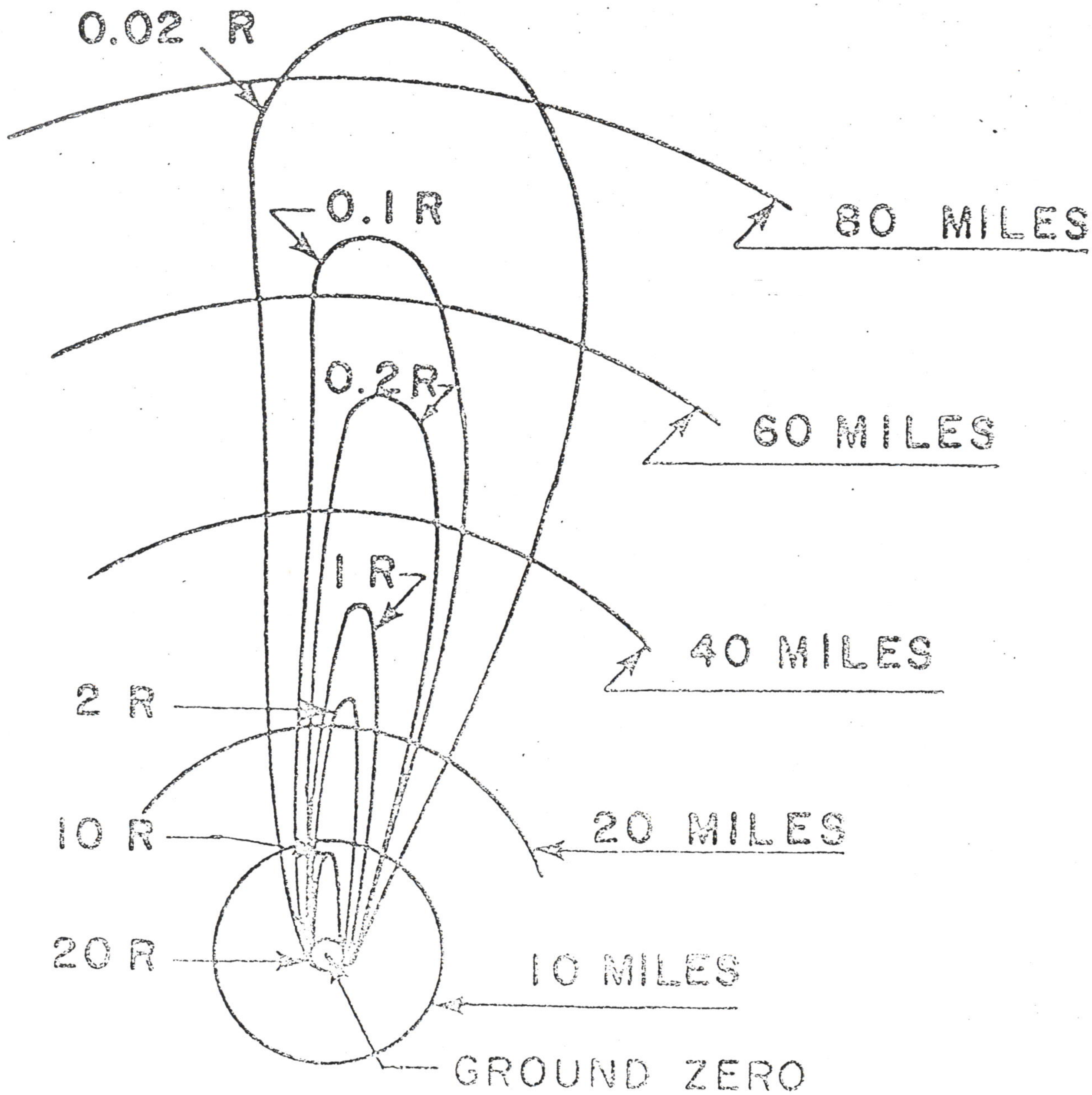
	Fission explosion				Fusion explosion					
	5 kt (3.5×10^3 kCi)		100 kt (7.0×10^7 kCi)		3-kt trigger (2.1×10^6 kCi)		100 kt (97-kt fusion)		1,000 kt (997-kt fusion)	
Radionuclide	A	B	A	B	A	B	A	B	A	B
H-3	0.005	1.10	0.1	22.0	0.003	0.66	0.0	[a]	0.0	[a]
C-14	0.0	0.0	0.0	0.002	0.0	0.0	0.0	0.002	0.0	0.023
Ar-37	0.0	12.5	0.0	250	0.0	7.5	0.0	700	0.0	7,000
Kr-85	0.10	0.0	2.0	0.0	0.05	0.0				
Sr-90	0.75	0.0	15.0	0.0	0.45	0.0				
I-131	725	0.0	14,500	0.0	435	0.0				
Xe-131	5.0	0.0	100	0.0	3.0	0.0				
Xe-133	1,650	0.0	33,000	0.0	1,000	0.0				
Cs-137	0.90	0.0	18.0	0.0	0.54	0.0				

[a] 100 kt, 28.0 + 1,940; 1,000 kt, 280.0 + 19,400 (latter figure in both cases indicates residual tritium at rate of 20,000 Ci/kt).

Barge, D.C., and King, W.C., (Reference 43)

TABLE II-VII

EXAMPLE INFINITE-ISODOSE CURVES
FOR A 100-KT EXPLOSION, 2-5 PERCENT
PROMPT VENTIVE RELEASE



Williamson, M.M., (Reference 44)

Delayed venting or seepage to the atmosphere should have a maximum percentage of radioactive material escaping of less than that of a prompt venting incident. Mixed fusion products decay by a factor of approximately 10 for every seven fold increase in time. Thus, the radioactive isotopes decay by a factor of 10 in the first hour after detonation, by another factor of ten after 7 hours, by another factor of ten after 2 days, and so on. Table II-VII lists the potentially volatile radioactive nuclides present 180 days after a 1,000 kt nuclear explosion in igneous rock. Maximum possible concentration of each nuclide in air and water is also given. The volatility of many of these nuclides in steam is dependent upon the chemical conditions present in the steam. This information is given in the final column of Table II-VII. Thus, the amount of radioactivity which could reach the atmosphere would be dependent not only upon concentration of nuclides in the cavity but also upon whether the nuclides are carried as gas or in steam or in water. It should be noted that although leakage is possible, there has been no recorded leakage of contaminants to the atmosphere from any size nuclear device detonated at a depth greater than 4,000 feet.

Contamination of ground waters is also unlikely, but could occur as a result of improper cementing of the drill hole or through faults of fissures in the surrounding rock. Verification that raioactivity cannot escape may be difficult because cementing technology at high temperatures is not developed.

Most ground waters flow at rates from 1 to 1000 feet per year. In general, radioisotopes would not travel as fast as the ground waters

TABLE II-VII

Potentially Volatile Radioactive Nuclides Present 180 Days After a 1,000-kt Nuclear Explosion in Igneous Rock

Nuclide	Half-life	Fission (kCi)	Fusion[a] (kCi)	RCG[b] (pCi/ml) Air	RCG[b] (pCi/ml) Water	Volatility in steam (80 atm, 623°K)
Kr-85	10.8 yrs	20	0.06	0.3	—	Permanent gas
Sr-90	28.8 yrs	150	0.45	3×10^{-5}	0.3	Gaseous precursor
Ru-103	40 days	1,150	3.45	0.003	80	Oxidizing, high; reducing, low
Ru-106	1 yr	1,000	3.0	2×10^{-4}	10	Oxidizing, high; reducing, low
Sb-125	2.7 yrs	60	0.18	9×10^{-4}	100	Apparently high
Te-127m	109 days	90	0.27	0.001	50	High
Cs-137	30 yrs	180	0.54	5×10^{-4}	20	With CO_2, low; without CO_2, high (30%)
			Radioisotopes Induced in Soil			
H-3	12.3 yrs	220	20,290[c]	0.2	3,000	As permanent gas and tritiated vapors
Na-22	2.6 yrs	—	0.6	3×10^{-4}	30	—
P-32	14.3 days	2	2.5	0.002	20	—
S-35	88 days	29	40.0	0.009	60	—
Ar-37	35 days	70	200	100	—	Permanent gas
Cs-134	2 yrs	14	18.3	4×10^{-4}	9	With CO_2, low; without CO_2, high (30%)

American Oil Shale Corporation. (Reference 45) because of sorbtion and dispersion processes. Tritium, however, is highly soluble in water and travels as fast as the water flow rate. Tritium, with a half life of 12 years, would be reduced one thousand fold in ground water flowing at 1000 feet per year after traveling 23 miles from the point of detonation. The above process would take about 120 years.

d. Power Production and Plant Operations

After nuclear stimulation of a hot, dry rock system the generation plant would be built. This would require drilling at least two holes into the nuclear chimney for the circulation of hot water for power production. The possibility of ground water contamination by migration of radioactive fluids along the bore holes has already been discussed.

The major environmental hazard involved in the production of power involves the volatile radioactive products that are not condensed in the cavity and are easily transported to the surface via the working fluid.

There are two ways in which a nuclear stimulated geothermal system can be utilized to produce power. Hot water can be brought to the surface and used to heat a secondary fluid which is then expanded to drive a turbine (see Chapter I). This system would return the radioactive fluid to the cavity, and radioactive gases would not come in contact with the ambient anvironment. The other method to produce power would use flashed radioactive fluids directly to drive a generation device. A power plant using this type of system would collect the radioactive non-condensable gases in the condenser. Condensate could be reinjected to the cavity, however, non-condensable gases might be vented to the atmosphere or, if the concentrations exceeded state or Federal Standards, radioactive gases could be compressed and stored or recycled to the cavity.

The use of a direct power system could result in contamination by deposition of radioactive materials on all machinery in the working fluid system. The risk of accidental release of radiation to the atmosphere is also increased in the direct utilization of radioactive steam. The use of a bifluid system would be more acceptable from an environmental point of view. However, plant efficiency would be lower and capital investment in machinery would be higher.

Regardless of which type of system is used, there is a chance of environmental contamination resulting from ruptured pipes, steam lines, and production and reinjection wells. In addition to radioactive materials, there is also a potential hazard from the release or escape of materials such as: CO_2, H_2S, NH_3, CH_4, and others discussed previously in this chapter.

The assessment of the environmental impact of nuclear stimulation of geothermal resources must be very extensive in scope and detail to adequately determine the potential for hazard from nuclear shock waves and radioactive materials. Direct exposure of persons and wildlife to radioactivity released by prompt venting is the greatest hazard. However, analysis should consider low level deposition and accumulation in plants and animals and secondary effects upon food pathways for animals and humans.

Chapter III

Recommendations for the Development of Geothermal Energy in Montana

A. Impact Statements

1. General
2. Geothermal Exploration Phase
3. Test Drilling Phase
4. Production Testing Phase
5. Full Scale Development Power Production

B. Specific Environmental Standards Pertaining to Geothermal Resources Development

1. Air Quality
2. Water Quality
3. Land Use
4. Noise

C. Conclusion: Geothermal Energy, Montana, and Environmental Quality

CHAPTER III

RECOMMENDATIONS FOR THE DEVELOPMENT OF GEOTHERMAL ENERGY IN MONTANA

GENERAL

The ultimate environmental impact of the development of geothermal resources in Montana will have a direct relationship to the legislation and regulation concerning the resource in Montana. Because Montana has not been forced to proceed as rapidly as other states in the regulation of this resource, it is possible to draw from their experience in the beginning solution to this complex problem of designing a system of regulation to which the industry is not unduly restricted while providing for the maximum protection of the environment. The author is not a legal expert, and as a result, these recommendations will be from a viewpoint of environmental adequacy.

In reviewing geothermal legislation in other states and on the Federal level, there does not appear to be a consensus as to the basic nature of the resource. Because the definition of the resource by the state is an important consideration in determining the degree and scope of regulation of the resource, it is necessary to consider several significant questions pertaining to the definition of the resource. In what catagory of minerals does it fit? Is it a solid, liquid, or gas, a combination of them, or neither? What, if any, application do the water laws of the state have? What are the incidents of its exploration, leasing, and production?

In the definition of this resource, the central idea is that it consists of the natural heat of the earth. Although geothermal energy may eventually be utilized from "dry" steam, "wet" steam, hot rocks, or magmatic sources, all derive their energy from the natural heat of the earth. It is apparent that all geothermal resources will not fit easily into any established pattern or form. Different manifestation, uses, and methods of use clearly separate them from present well-defined patterns of resource definition.

The Federal Geothermal Steam Act of 1970 defines the resource as follows:

> "Geothermal steam and associated geothermal resources means (i) all products of geothermal processes, embracing indigenous steam, hot water and hot brines; (ii) steam and other gases, hot water and hot brines resulting from water, gas or other fluids artificially introduced into geothermal formations; (iii) heat or other associated energy found in geothermal formations; and (iv) any byproduct derived from them."[1]

In contrast, the California Resource Act of 1967 defines geothermal resources as:

> "...'geothermal resources' shall mean the natural heat of the earth, the energy, in whatever form, below the surface of the earth present in, resulting from, or created by, or which may be extracted from, such natural heat, and all minerals in solution or other products obtained from naturally heated fluids, brines, associated gases, and steam, in whatever form, found below the surface of the earth, but excluding oil, hydro-carbon gas or other hydrocarbon substances."[2]

New Mexico's definition of geothermal resources is almost identical to the above. The Geothermal Steam Act of the state of Oregon defines geothermal resources as:

> "The natural underground reservoirs of heat that may be exploited for the production of heat energy, including but not limited to all minerals obtained from naturally or artificially injected fluid, brine or associated gas and steam in any form whatsoever, but excluding oil hydrocarbon gas and other hydrocarbon substances and hot waters of less than 250 degrees Fahrenheit bottom hole temperature."[3]

In Montana at present it would appear that water is defined to include "geothermal water". Subjecting geothermal resources to the water laws of the state may preclude the development of geothermal resources in this state. Water laws have not developed in contemplation of geothermal resources. Their scope and purpose do not fit the projected utilization of the resource.

It is necessary to recognize that geothermal resources are separate and unique and should be handled as such in the development of general regulatory organization of the resource, legislation, and promulgation of rules and regulations pertaining to geothermal energy. It would be unwise to regulate this new energy resource with any one existing regulatory discipline, as its benefits can include power production, water, minerals, and heat for a number of needs. However, the creation of a special geothermal agency would necessitate duplication in several areas. Thus, it is the authors opinion that a system of regulation in all phases of geothermal operations be administrated by several agencies with jurisdictional power in each agency's particular area of specialization.

This type of administration could give rise to a system whereby the developer(s) of a geothermal resource area would have to obtain a permit from each agency involved in the regulation of the resource. This situation should be avoided as it creates undue repetition and cost for the developer and for regulating agencies. For this reason, it is suggested that one agency be designated the prime regulatory agency which would issue all operations and construction permits other than those required by previous law (e.g. M.E.P.A. or the Montana Utility Siting Act). An inter-agency control board would be created to insure, among other things, that there is adequate inter-agency organization for the communication of information between the prime regulatory agency and other involved agencies.

A system similar to that of California would appear to be the most flexible, least costly arrangement to provide for the maximum control of the development of the resource. A similar system for the administration of the energy resource would have organization as follows:

1. The Oil and Gas Conservation Division of the Department of Natural Resources and Conservation would be designated the prime regulatory agency. This agency has the necessary expertise and experience gained through its history of regulating the petroleum industry. Because of the similarity between the petroleum industry and geothermal exploration and development, this agency appears to the best equipped to oversee operations. This department would, in general, be responsible for well operation, environmental and subsidence control.

2. The Energy Planning Division of the Department of Natural Resources and Conservation would be responsible for power plant siting as directed by the Montana Utility Siting Act of 1973 Sections 70-803 to 70-823 of the R.C.M., 1947 which have been recently amended to provide for the inclusion of geothermal resources into the act.[4]

3. The Department of State Lands would be is? responsible for the leasing of state lands for the purposes of the development of geothermal resources.

4. Geothermal Geologic Studies necessary for geologic impact and resource evaluation would be conducted by the Montana Bureau of Mines and Geology or by contributing institutions of higher education.

5. Evaluation and regulation of air pollutants would come under

the jurisdiction of the Air Quality Bureau, Department of Health and Environmental Sciences.

6. Evaluation and regulation of water pollutants would be vested in the Water Quality Bureau, Department of Health and Environmental Science.

7. Hydrologic studies would be conducted by the Water Resources Division, Department of Natural Resources and Conservation. It should be noted that the Water Quality Bureau is in the process of promulgation of water quality standards for ground waters, thus the regulation of ground water quality would be vested with the Bureau. It is possible that the Water Quality Bureau could also conduct hydrologic surveys. This duty should be delegated on the basis of ability and experience, as well as the willingness for administrative involvement.

8. The Public Service Commission would regulate the geothermal facility, if used for power production, in the Commission's present regulatory capacity concerning operations and power rates.

9. A Geothermal Resources Board would be created to coordinate geothermal development in the state of Montana in a manner which would insure the most orderly and beneficial use of geothermal resources while maintaining environmental quality at the highest possible level. The board would organize the promulgation of regulations within each administrative agency to insure that all areas of regulation are sufficiently covered. The Board would meet on a regular basis to insure that the prime regulatory agency and other contributing agencies are maintaining adequate intra-governmental communication to insure efficient control of the resource. The Board would consist of one member of each

agency previously listed.

The development of this type of organization in the state of Montana will, of course, require the promulgation of legislation to lease and control the geothermal resources in the state. In the development of this legislation there are several major factors which should be included to insure maximum financial and environmental protection of the state and its resources. Major points to be considered include the following:

1. To claim the right to regulate the development and use of all of the geothermal resources within the state. This type of stipulation would insure that the state would participate in the development of all areas of land on which the resources are found, be it on state, private, or Federal property.

2. The code should provide for the protection of life, health, property, and natural resources of the state through the sound regulation of drilling, production, maintenance and abandonment of wells. Authority should also be delegated to control subsidence due to geothermal development. These stipulations and regulations must be provided for in geothermal resource legislation either by direct inclusion or by directing different departments to promulgate and adopt regulations for the orderly development of the resource.

3. A geothermal code should require the filing of certain data gained by the operators with the prime regulatory agency so that controlling agencies can best regulate the development to insure the most beneficial and least destructive use of the land and its resources. This information would include geophysical data, a drill

log, representative data or samples of drill cuttings or cores, and a history of the drilling of the well. A log should include the character and depth of each formation, size and type of casing used and the location, depth, temperature and composition of fluids encountered. All data and information submitted to the prime regulatory agency should be organized and distributed by the prime regulatory agency to appropriate administrative agencies in the state government.

4. Geothermal legislation should include a requirement for a drilling fee to finance the operation of staff of the Oil and Gas Conservation Division required to regulate geothermal operations. Further, a bond should be required to indemnify the state in the event that costs are incurred in the repair or abandonment of wells deserted by operators.

5. A provision to lease state lands for geothermal development should be considered.

Annual rental and royalty revenues have been projected to reach $270,000 dollars per year at the Gysers Field by 1974-75.[5] If the 18,000 acres of state land leased in that area for geothermal production were to be fully developed, the area could produce $600,000-700,000 annually in state revenue.

The basic requirement of a leasee operating upon state lands should be to take all reasonable precautions to prevent all types of adverse environmental impact. Leasing and operating regulations should provide for the termination of the lease after due notice for failure to comply with leasing and operating regulations, including failure to provide environmental protection. When the leasee fails to comply with leasing and operating regulations, the prime regulatory geothermal resources board should have sufficient power to suspend certain operations and give notice to correct faults or violations. Failure to remedy the required action should result in suspension of all operations and eventual cancellation of the lease.

Certain state lands should be excluded from geothermal leasing. These areas would be of character or land use value which cannot mutually exist with geothermal resource development. Such areas would include: parks, fish hatcheries, historic sites, archeological sites, wildlife refuges, water fowl production areas and certain areas of high aesthetic value.

6. Geothermal legislation should call for the creation of a geothermal resources board made up of persons heading agencies regulating the development of the resource. This board should direct itself toward the orderly development of the resource. It should further organize the regulating agencies in the promulgation of administrative procedure subsequent to the act itself.

MONTANA CODES APPLICABLE TO THE ENVIRONMENTAL IMPACT OF GEOTHERMAL DEVELOPMENT

A. Impact Statements

1. General

In general, the Montana Environmental Protection Act and its Revised Codes and the Montana Utility Siting Act as amended by the 43rd Legislature provide for the development of an adequate environmental impact statement to assess the impact of geothermal development. However, there appear to be a few areas in which these acts are not specific to certain points.

Because geothermal developments proceed on a step-by-step basis, with further development dependent upon the success of the previous step, it is not definite at which point in time an impact statement would be required. For example, the Marysville project has proceeded through the exploration phase and is proceeding through the test drilling phase. There are certain impacts and environmental risks involved in both of these stages of development. However, the State Department of Natural Resources has not requested an environmental impact statement for either step. This does not appear to be an adequate arrangement to insure the maximum degree of environmental and resource control.

Marysville on Feder land - wou the be ref to?

also, they have filed impact statement w/ Feds?

Because geothermal development is a lock step procedure, it is difficult at the outset to determine whether or not a major commitment of resources is likely to follow. However, it would not be prudent to ignore the impact statement procedure until a major field development is indicated. It is suggested that anyone involved in the development of geothermal resources provide a brief impact statement for the phases of exploration test drilling and a more complete report for production testing. The entities conducting these phases of operation are often not integrated companies with large amounts of capital and staff available for writing impact statements which would include all phases of development. Further, at these levels of development there is generally insufficient data to make long range predictions as to impact. Thus, if impact statements were required for the entire development at the test drilling phase, the nonavailability of data and financial burden of statement preparation could result in the discouragement of the development of geothermal resources in Montana which, by many parameters, appear to have a lesser impact upon the environment than many other forms of energy sources and conversion.

2. Geothermal Exploration Phase

Exploration upon state lands would have to comply with present state rules and regulations regarding this subject. The type and scope of information necessary in an impact summary for geothermal exploration would be largely dependent upon the area in which exploration was to be conducted (e.g. roadless or wild versus an area easily accessible by vehicle) and the type of explorative methods used (e.g. active seismic versus remote sensing). The summary should include a description of explorative devices to be used, the length of operation, alterations of the land surface and use necessary, visual impact, and the possible impact of activity upon residents and/or wildlife.

3. Test Drilling Phase

A summary of the impact of test drilling should include the type of geologic structures and geothermal resources indicated by explorative information. Other important data would include requirements for road building, site preparation, and general land use. During this phase strict control of drilling is necessary to insure the prevention of blowouts and/or casing breaks which could result in significant air, surface water, and ground water degradation.

4. Production Testing Phase

The production testing phase requires an even greater degree of control. The release of geothermal fluids to the atmosphere or surface waters could result in acute degradation and violation of standards. Thus, prior to testing, data concerning the temperature, chemistry and physical nature of geothermal fluids, should be submitted to the prime regulatory agency and distributed in the Department of Health and Environmental Sciences. Other data to be submitted could include anticipated effects upon air quality by non-condensable gases and particulate, meteorological considerations, adverse effects upon water quality by geothermal waters in terms of both thermal and chemical degradation, and the expected levels of noise and their possible adverse effects. The Department of Health and Environmental Sciences would review information and issue short term water and/or air discharge permits for this phase of development. The Department of Health and Environmental Sciences monitors or requires private monitoring of all discharges.

5. Full Scale Development and Power Production

If all previous phases of geothermal resources development prove successful and full scale development of a geothermal area is indicated, a full environmental impact statement would be required by the Montana Environmental Protection Act and, if of sufficient size or cost an intensive study would be required by the Montana Utility Siting Act of 1973 as amended by the 43rd Montana State Legislature.

The information required by these sections of the Revised Codes of Montana are sufficient to gather adequate impact information.

B. Specific Environmental Standards Pertaining to Geothermal Resource Development

1. Air Quality

Montana Ambient Air Quality Standards, Regulation 90-105, describes ambient standards for a number of air pollutants. Those which pertain to geothermal resources development would include: Hydrogen Sulfide, Total Suspended Particulate, Settled Particulate, Fluorides, and Beryllium. The oxidants of Hydrogen Sulfide could also be considered applicable in part, to geothermal resources. It is apparent from chemical analysis of geothermal waters that geothermal operations could produce sufficient amounts of some elements or compounds so as to cause chronic or acute environmental damage. Chemicals present in geothermal fluids which are most likely to cause this type of damage would include carbon dioxide, carbon monoxide, ammonia, and mercury. Of these, ammonia, carbon dioxide, and mercury have no applicable Federal ambient standards. The Occupational Safety and Health Act has set the following standards for human exposure:

Substance	P.P.M.
Ammonia	50
Carbon Dioxide	5,000
Mercury	1 mg/10m^3

However, these are not ambient standards and pertain only to in plant human exposure. Protective devices can be used to avoid these contaminants. Environmental damage could occur from these contaminants and thus, it may be necessary to create ambient standards for these chemicals. Further research is necessary to establish primary and secondary standards for the discharge of mercury.

Other chemicals which could cause environmental damage would include As, B, Ar, and certain radionucleides. Of these, only the radionucleides are controlled for human and environmental exposure. This is done by the Atomic Energy Commission.

The State of Montana has promulgated standards for the discharge of radionucleides into surface waters, however, there are presently no standards for the discharge or leakage of radioactive materials into ground waters or into the air. Prior to approval of a geothermal nuclear stimulation project, standards concerning air and ground water contamination should be promulgated.

Geothermal fluids vary greatly in the content and concentration of chemicals. As a result, each geothermal project will have to be individually evaluated to ascertain if its chemical content is a potential problem as a basis for establishing control measures, stipulation, or standards. In the creation of geothermal regulation in Montana, controlling agencies should be given adequate provision to deal with potentially harmful chemicals not presently under control.

2. Water Quality

Water Quality Standards for Montana as written in MAC 16-2.14 (10)-514480 appear to be adequate to protect the surface waters of Montana. Although the standards do not contain specific criteria for certain chemicals present in geothermal waters there is sufficient provision in the code to protect surface waters from the large variety of deleterious substances which may be present in geothermal waters.

Ground waters do not, at present, appear to be sufficiently protected from degradation by geothermal sources or other sources. Underground waters are classified as "state waters" in 69-4802 R.C.M., 1947. Further, the classification of all waters is required in 69-4804.2 R.C.M., 1947 which reads as follows:

> "Duties of the board of health. (1) the board shall: (a) establish and modify the classification of all waters in accordance with their present and future most beneficial uses; (b) formulate standards of water purity and classification of water according to its most beneficial uses; giving consideration to the economics of waste treatment and prevention;"

At present, the only Montana law which concerns itself with the pollution of underground waters is 89-2926 R.C.M. which reads as follows:

> "... The administration shall require all wells producing water which contaminates other waters to be plugged or capped. He shall also require all flowing wells to be capped or equipped with valves such that the flow of water can be stopped when the water isn't being put to beneficial use."

Although this section would protect high quality aquifers from degradation by geothermal waters eminating from a well, it does not assure protection of underground waters from pollution by reinjection or other geothermal activity.

The Water Quality Bureau is in the process of promulgating water quality standards for ground waters. This process will take from one to two years.[1] These standards should be reviewed, prior to approval, to insure that they adequately protect groundwater quality from: (1) surface seepage of geothermal waters into high quality ground waters, (2) degradation of underground waters by reinjection, (3) degradation of underground waters by faulty or broken well casings, and (4) degradation of underground waters by other causes induced by geothermal activity (e.g. subsistance, or industrial use of geothermal waters).

3. Land Use

Land use in the vicinity of geothermal developments will be changed by the construction of roads, wells, pipelines, powerlines, power plants and other facilities associated with geothermal development. Where and if the state provides for the leasing of state lands for geothermal development, land use considerations should be required. Land use considerations should also be accounted for in areas on and adjacent to privately owned geothermal development. In the lease of state lands, certain sreas should be excluded from lease potential. These include, but are not limited to: parks, recreation areas, fish hatcheries, wildlife refuges, game range lands, waterfowl areas, production and habitat areas of endangered species, historical sites, and archeological sites. In addition, areas adjacent to geothermal resources should be considered in the granting of leases in such cases where the incompatibility of land uses is irreconcilable.

Comprehensive planning beginning with the first stages of leasing continuing through full scale operations would contribute greatly to harmonious layout, design, and land utilization. Leases should include provisions that geothermal facilities should be designed to the greatest extent possible to blend harmoniously with its surroundings. This may require the promulgation of such architectural and layout standards by the Department of State Lands.

4. Noise

At present, the state of Montana does not have standards regarding the production and control of noise. To protect workers and to keep the environmental impact of noise at a minimum, the regulation of noise would appear to be prudent.

Federal noise exposure levels have been established pursuant to Section 6(a) and 8(g) of P.L. 91-596, "The Occupational Health and Safety Act of 1970". However, this applies only to workers and is not adequate to provide for minimal noise impact.

Geothermal development standards have been adopted by Imperial County, Claifornia, and have been proposed for other California counties. These standards include provisions for noise abatement and are included in appendix .

C. Conclusion: Geothermal Energy, Montana, and Environmental Quality

The technology of geothermal resources development is proceeding at an ever increasing rate. This is a result of increasing energy and environmental costs associated with alternative energy sources such as nuclear or fossil electrical production. Any development of geothermal energy will result in solid, gas, liquid, or thermal waste which must be disposed of. The state of Montana should have the administrative ability to follow the development of geothermal resources technology and to use this information, with its power to set standards, to stimulate the use of technology which would create minimum adverse environmental impact. It is also necessary that regulations and codes designed to stimulate such environmental technology do not create a sufficient disincentive to prevent the development of geothermal technology with overall advantages over conventional alternate resources. Further analysis of geothermal energy should stress the contrasts between the impacts associated with geothermal energy and its conventional alternatives of fossil and nuclear generation. This would allow the state to weigh the advantages and disadvantages of each power source and apply decisions for or against future energy options on the basis of overall benefits and environmental impact. It is clear that the state of Montana will require a geothermal resources act to provide for the leasing, orderly development, and environmental protection of the state. The consideration and drafting of such provisions should commence as soon is possible.

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